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Engineering Test Unit and Controls

Integrated Orbital Servicing Study Follow-on

MARTIN MARIETTA

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INTEGRATED ORBITAL SERVICING STUDY FOLLOW-ON

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FOREWORD

This study was performed under Contract NAS8-30820 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration under the direction of James R. Turner, the Contracting Officer's Representative. The final report consists of three volumes:

Volume I - Executive Summary
Volume II - Technical Analyses and System Design
Volume III - Engineering Test Unit and Controls

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I. INTRODUCTION AND SUMMARY

The concept of orbital servicing in the form of module exchange as a method of repairing spacecraft in orbit has been receiving increasing attention in the aerospace community as a viable and useful activity over the last few years. Module exchange can be applied to spacecraft repair, updating and replacement of mission equipment, and resupply of expendables. These functions are pertinent to spacecraft or satellites, public service platforms, and solar power stations whether in high or low earth orbit. Many of the techniques and methods can be useful in the assembly of large space structures and other repetitive operations in space. Under the direction of the NASA Marshall Space Flight Center, Martin Marietta Corporation's Denver Division has designed, manufactured, assembled, checked out, and delivered a one-g servicing demonstration system (Figure I-1) which can be used to investigate and develop--in a real-time hands on situation--a wide variety of the mechanism and control system aspects of module exchange.

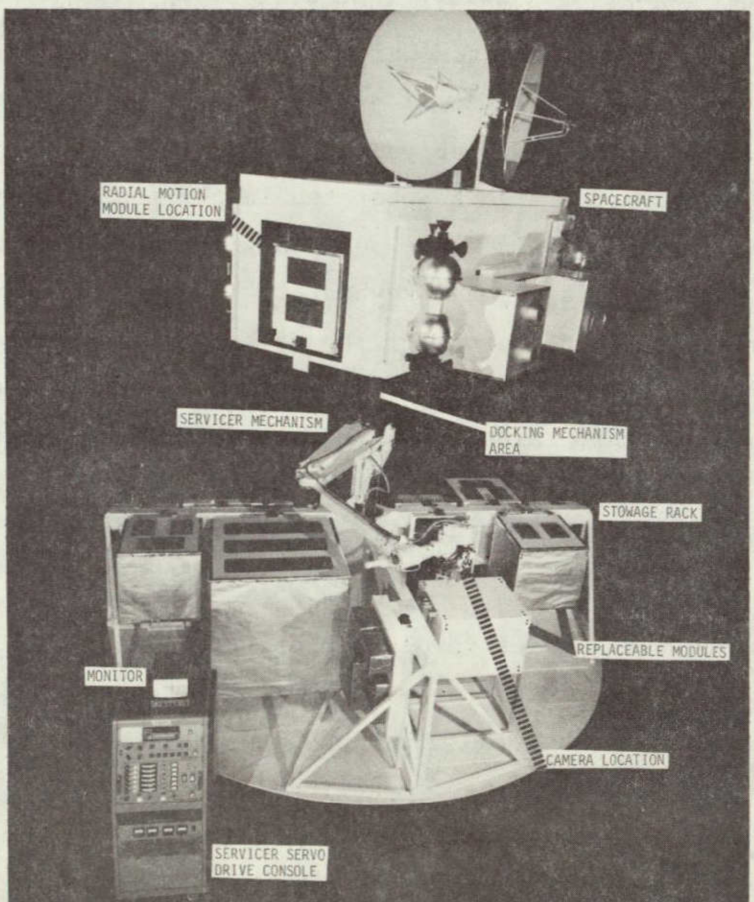


Figure I-1 One-g Servicing Demonstration System

The one-g servicing demonstration system is made up of--1) a one-g servicer mechanism, 2) a servicer servo drive electronics console, 3) two replaceable module mockups, 4) a 15 ft diameter stowage rack mockup containing passive replacement modules, 5) a representative spacecraft mockup shown docked to the stowage rack, and 6) a closed circuit television system. This equipment is complemented by a digital computer with input/output equipment (not shown), and a control station (not shown). The demonstration system is functionally and geometrically equivalent to the servicing system recommended for flight use in an earlier part of the contract. Thus transfer of knowledge gained with the demonstration system to the flight system will be straightforward.

The one-g servicer mechanism has six degrees of freedom, is servo powered, counterbalanced, and has a seven-ft operating radius. The SSDC is a self-contained electronics system which contains all the functions for operation of the system in a direct joint-by-joint manual control mode. When complemented with a suitably programmed digital computer and control station, the system can also be operated in the supervisory and manual augmented control modes. In the supervisory mode, the operator interfaces with an alphanumeric display and keyboard. The mechanism goes through the module exchange trajectories under the control of the computer. In the manual augmented mode, the operator interfaces with a set of hand controllers and the closed circuit television system. The operator controls the mechanism with the computer transforming his hand controller inputs to mechanism joint inputs so they are always coordinated to the TV display.

Each of the two replaceable modules involves a different form of interface mechanism which is the structural attachment between the module and spacecraft or stowage rack. The side mounting interface mechanism operates like a drawer slide while the base mounting interface mechanism operates more like placing a box on a desk. The active module locations in the stowage rack are in the right front quadrant of the figure

and involve axial (parallel to the docking axis) module motion. The spacecraft mockup has two axial module motion active locations (minimum and maximum radius) which do not show in the figure and one radial (perpendicular to the docking axis) module motion active location. The CCTV system involves the monitor shown on top of the SSDC and a solid state TV camera with auto-iris lens mounted near the mechanism end effector.

The one-g servicing demonstration system activity was a significant part of contract NAS8-30820 and was completed over a 22-month time span. The objective of this phase was to design, fabricate, test, and deliver certain equipment for the conduct of one-g demonstrations of axial and radial module exchange in three control modes. The three control modes are:

Supervisory - This is the normal mode of operation. All servicer mechanism motions and trajectories are determined beforehand and stored. The computer implementing this mode will sequence from one segment of the trajectory to the next, but only when the man has evaluated the state and provided a "go".

Manual Augmented - This mode has man doing most of the mechanism control using hand controllers. The computer is in the loop to facilitate the direction of motion of the mechanism and provide coordination of its motion with respect to the displays provided. Its most useful role is to perform unscheduled motions to previously unidentified targets of opportunity and corresponds closely to the usual methods for control of a manipulator by an operator.

Manual Direct - This mode is provided as a totally unsophisticated means of backup control. It sends commands directly to the joints themselves. Commands are one joint at a time. Motion is with respect to each joint's mounting base rather than with respect to the display coordinate system. Its uses are--1) as a possible normal control mode for certain simple arm configurations that lend themselves to direct

joint control; 2) as a backup in the event of a failure in the computations; or 3) in the event a joint failure has occurred that can be worked around, but the computerized coordinate transformations either onboard or on the ground are not valid. No computational, control, or display equipment other than the SSDC is required to use this mode.

The above three control modes should not in any way be construed to be the final selection for an ultimate servicing system. They have been chosen to span the spectrum of sophistication of the types of control envisioned for servicing. Final recommendations will evolve from the evaluations and testing to be performed with the one-g servicing demonstration system at MSFC.

Demonstrations of system operation in all three control modes for both side and base mounting interface mechanisms and exchanging modules in both the axial and radial directions were conducted at the Denver Division of Martin Marietta Corporation in February 1978. These demonstrations proved the ability of the deliverable equipment to satisfy the stated goals in a most effective manner. A Martin Marietta computer was used for these demonstrations. Subsequently, the equipment was delivered to MSFC, assembled, checked out, and demonstrated. The system is scheduled for familiarization operations and is then to be used to evaluate spacecraft orbital servicing system alternatives leading to a set of requirements for flight system development by way of a protoflight servicing system.

The balance of this report describes the One-g Servicing Demonstration System, the Engineering Test Unit, and the Servicer Servo Drive Console. The final chapter provides a series of recommendations for future work. The first group of recommendations leads to a better understanding of the control problem and more efficient module exchanges. The second group addresses improvements to the mechanical elements, particularly the shoulder pitch and wrist yaw drives. The last group of recommendations involves improvements in the electronics including the joint brake release system.

Additional data relative to the one-g servicer demonstration system activities are contained in the following documents.

Integrated Orbital Servicing Study Follow-On, Design Acceptance Review, February 1978, Martin Marietta Corporation, Denver, CO.

Servicer Simulation Software Requirements, Revision C, February 27, 1978, Martin Marietta Corporation, Denver, CO.

Servicer Servo Drive Console Design Requirements, Revision B, March 3, 1978, Martin Marietta Corporation, Denver, CO.

SSDC Electronics Identification, March 15, 1978, Martin Marietta Corporation, Denver, CO.

One-G Servicer System Operating Procedures, March 14, 1978, Martin Marietta Corporation, Denver, CO.

A nine minute, silent, color motion picture film showing radial module exchange in the supervisory control mode was prepared.

II. ONE-G SERVICING DEMONSTRATION

The Engineering Test Unit (ETU) of the on-orbit servicer mechanism when combined with the controls system has been designed to provide MSFC with an advanced full-scale facility for the development of on-orbit servicing systems. The counterbalanced servicer mechanism operates with both the side mounting and the base mounting interface mechanisms, can exchange modules axially from the stowage rack and both radially and axially from the spacecraft mockup, has a full six degrees of freedom, and is adaptable to the investigation of a wide range of electromechanical problems. A basic control system is provided by the Servicer Servo Drive Console (SSDC). The SSDC permits investigating manual direct methods of module exchange and provides an effective method of servicer system checkout and problem diagnosis. When interfaced with a suitable digital computer and program, the one-g servicing demonstration system provides a most effective tool for the investigation of all types of control systems including the supervisory and manual augmented modes. The digital computer permits rapid change of control law constants, trajectory sequences, operator displays, and coordinate system transformations. The computer may also be used for data collection and processing so experiment results may be made available sooner and more readily communicated to others.

Figure II-1 shows the major elements of the spacecraft servicing demonstration facility at MSFC and as established at Martin Marietta-Denver for the preliminary demonstrations. All equipment is common for the two demonstrations except for the control station and the digital computer which will be individually provided by the two facilities. The servicer mechanism structure is electrically powered and mechanically counterbalanced. It is servo controlled, fully integrated into the control system, operates very smoothly, and is capable of going from axial to or from radial module removal with no special setup time. It is a high quality, precision mechanism, which incoporates advanced design, rigid, low-backlash rotary joint drives. Two versions of interface mechanisms are provided--

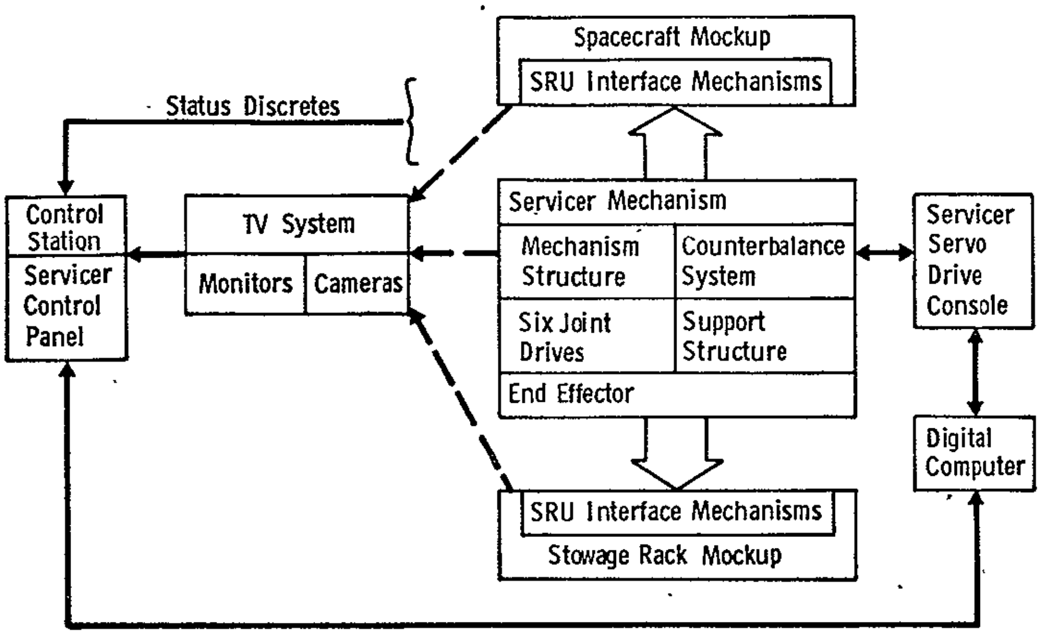


Figure II-1 Spacecraft Servicing Demonstration Block Diagram

side and base mounting. They can be used interchangeably in the three module locations of the spacecraft mockup (two axial and one radial) or the many module locations of the stowage rack. The single end effector works with both styles of interface mechanism.

The spacecraft and stowage rack mockups have been made soft in the appearance areas to minimize cost and maintain adaptability to change. However, they are hard and fully functional with regard to the interface mechanism receptacles and supports. A small size, light weight solid state TV system with auto-iris lens was included to provide a short focal length with good depth of field.

The servicer servo drive console (SSDC) is a fully self-contained electronics system that incorporates the DC power supplies, servo power amplifiers, signal processing electronics, six-degree-of-freedom servicer control panel, servo drive panel, and a digital voltmeter. The servicer control panel can be used locally as part of the SSDC or remotely as part of a control station. Interconnecting cables to the digital computer, the remote servicer control panel, and to the ETU are part of the facility. The status discretes from the spacecraft and stowage rack mockups provide information

on interface mechanism engagement and latching.

The ETU and SSDC should be considered as the first step in an evolutionary process and will be updated and expanded in capability as the problems become better understood and as the flight article configuration of the on-orbit servicer system becomes more definite. Of the large number of activities planned for these demonstration facilities, the most pressing include--man/machine interactions, structural stiffness effects, visual systems, mechanism and spacecraft capture volumes/tolerances, and control system performance.

A. CAPABILITIES

Selection of the best configuration of the ETU in terms of segment lengths, drive power, and number of degrees of freedom was addressed in an earlier phase of the contract. The factors considered are listed in Table II-1. The dilemma was to have the same configuration for the ETU and the space design yet to stay within reasonable economic bounds. The probability of successful demonstrations is much greater for the shorter arm lengths and fewer degrees of freedom of the axial configuration. However, the sixth degree of freedom is necessary to be able to go from axial to radial module exchange with no change in setup. The shorter arms of the axial configuration were made compatible with radial module removal by having part of the spacecraft mockup extend out to the fifteen foot diameter of the Orbiter cargo bay and another part at a diameter that will permit investigation of radial module removal for reasonably sized modules.

Servicer mechanism arm length is a particularly important parameter in that it affects so many things which increase costs and required accuracy. These parameters include joint drive torque level, output gearing accuracy, gear housing machining accuracy, feedback sensor accuracy, servo loop gains and compensation, arm segment stiffness, electronic grounding and signal shielding, as well as system calibration.

As the primary element of a complete on-orbit servicing demonstration

Table II-1 Engineering Test Unit Configuration Selection Considerations

- PREFER TO HAVE THE ENGINEERING TEST UNIT REPRESENT THE CONFIGURATION OF THE SPACE DESIGN
- NEED TO KEEP THE DEMONSTRATIONS SIMPLE
  - Gives more confidence to user
  - Increases probability of good demonstrations
- THE SIMPLER THE ENGINEERING TEST UNIT, THE HIGHER THE PROBABILITY OF SUCCESSFUL DEMONSTRATIONS
  - Arm Length
  - Degrees of Freedom
  - Module Removal Directions
  - Variety of Interface Mechanisms
  - Number of Tasks to be Demonstrated
- PREFER TO DEMONSTRATE RADIAL AS WELL AS AXIAL MODULE REMOVAL
- PREFER TO HAVE BOTH BOTTOM AND SIDE MOUNTING INTERFACE MECHANISMS INVOLVED
- WANT TO BE ABLE TO GET POTENTIAL USERS INVOLVED
- MUST KEEP OVERALL SIZE TO FIT WITHIN SPACE AVAILABLE
- DESIRE TO ACCOMMODATE EXTENSION AND EXPANSION OF THE ENGINEERING TEST UNIT IN THE FUTURE AS IT IS USED IN THE DEMONSTRATION FACILITY

facility, the one-g servicing demonstration system has the potential of being very useful. A number of representative specific areas of utility are shown in Table II-2. These investigative areas have been addressed on the basis of design layouts and analysis in earlier studies, yet many of them are problems in dynamics that are difficult to solve analytically. The conventional and useful approach to studying these dynamics and man/machine problems is an iteration of analysis and simulation/demonstration. By working back and forth between analysis and experiment, the development process becomes more efficient and more real.

Table II-2 Utility of One-G Servicing Demonstration System

PRIMARY ELEMENT OF A COMPLETE ON-ORBIT SERVICING DEVELOPMENT FACILITY	
PROVIDES A FUNCTIONAL REPRESENTATION OF THE SPACE DESIGN	
DISCOVERY, REFINEMENT, AND EXPANSION	
PERMITS --	
MECHANICAL DESIGN EVALUATIONS	CONTROLS SYSTEM EVALUATIONS
Force and Torque Levels	Control Variables
Structural Stiffness	Capture Volumes
Backdriveability	Structural Stiffness Interactions
Interface Mechanisms	Trajectory Generation
Guide Configurations	Hazard Avoidance
Degrees of Freedom	Visual Systems
Motion Restrictions	Remotely Manned Backup
ONE-G TEST AND CHECKOUT EFFECT INVESTIGATIONS	
INCREASES CONFIDENCE IN THE SPACE DESIGN	
TIMELY AND COST-EFFECTIVE APPROACH TO ON-ORBIT SERVICING DEVELOPMENT	
PROVIDES FOCUS FOR ENCOURAGING USER ACCEPTANCE	

In the larger view, the servicing demonstration facility will become the focus for much of the servicing technology work. Its activities will parallel and complement servicer flight article development. Both technology and development are essentials of the long range implementation plan. As specific technological problems are identified in the development activity, they will be addressed in the demonstration facility. This facility will also provide a focus for encouraging user acceptance. It is physical evidence that NASA is following a long range plan in orbital maintenance. The users can have their specific problems addressed and thus gain confidence that their problems have acceptable solutions. As the specific needs of a number of users are collected and evaluated, the future of the servicing development can be shaped in terms of specifications, options, schedules, launch sites, and numbers of units that will be needed.

The servicing demonstration facility is integrated into the existing EC teleoperator facility at MSFC, which has a digital computer with the necessary interface equipment and software to be able to readily accept the ETU. The ETU and SSDC were installed in a high bay room that was expressly constructed for them. The manipulator part of teleoperator technology is

quite closely related to servicing system technology except that teleoperation activities are more general in nature, while the servicing system has been designed to suit the limited number of functions required by servicing activities. The cross fertilization of ideas, available equipment, and efficient use of personnel makes the EC teleoperator facility a good location selection.

The system specific characteristics of the one-g servicing demonstration system are listed in Table II-3. These characteristics respond to all the considerations of Table II-1 and represent an excellent compromise where the considerations pointed in different directions.

Table II-3 One-G Servicing Demonstration System Characteristics

- Good representation of flight unit design
- Simple system
- Full scale
- Counterbalanced
- Six degrees of freedom
- Axial module exchange
- Radial module exchange
- Precise, smooth drives
- Compatible with three control modes
  - Supervisory
  - Manual direct
  - Manual augmented
- Servicer control panel
- Servicer servo drive console
  - Servo drive panel
- Digital computer connections
- Spacecraft mockup
- One tier capability
- Stowage rack mockup
- Side-mounting interface mechanism
  - One baseplate
  - Three receptacles
- Base-mounting interface mechanism
  - One baseplate
  - Three receptacles

B. DESCRIPTION

The major elements and areas involved in a servicing demonstration facility are shown in Figure II-2. At the level of the figure, both demonstration facilities look the same. Differences are in terms of specific computers, interface electronics, control stations, and alphanumeric display devices. The functions performed by the computer are shown on the figure. A SEL840A computer was used at MSFC and a PDP 1145 computer with microprocessor interface electronics was used at Martin Marietta. The SSDC,

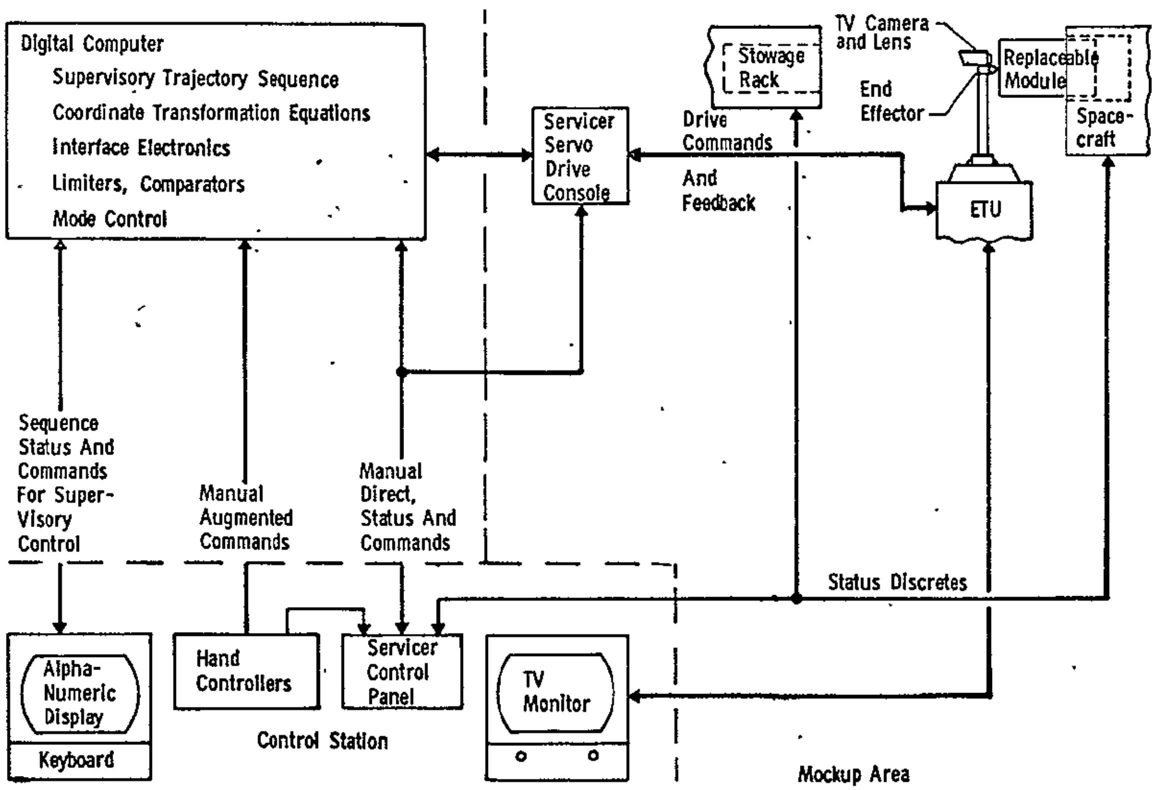


Figure II-2 Demonstration Facility Block Diagram

mockups, and ETU were located in the mockup areas. For the Martin Marietta demonstrations, the mockup area was in the Space Operations Simulator (SOS) laboratory, while for the MSFC demonstrations the mockups were located in Room A122 of Building 4487. The control station location for the Martin Marietta demonstration was a full-scale mockup of the aft flight deck of the Orbiter including the Payload Specialist's Station (PSS). The PSS was located in the SOS adjacent to the other mockups. At MSFC the control station was located in the EC teleoperator laboratory which is adjacent to Room A122.

Installation drawings for the ETU were prepared. A portion of one drawing is shown in Figure II-3. Similar arrangements of components were used at MSFC and at Martin Marietta so the checkout data, calibrations, and module location data could be directly transferred to the MSFC situa-

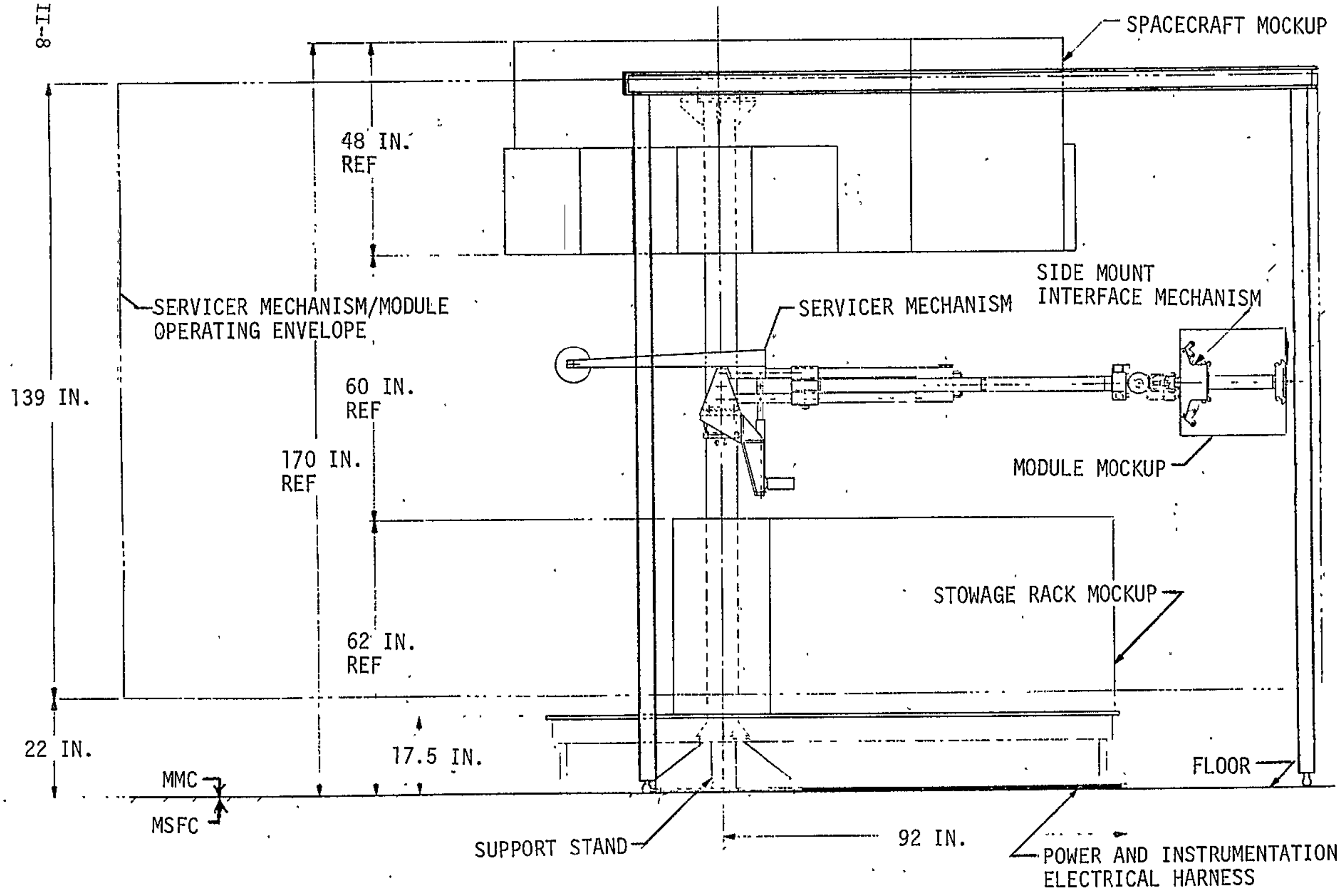


Figure II-3 Engineering Test Unit Installation

tion. The support stand provides the primary mechanical interface to the facility. It supports both the ETU and the spacecraft mockup. The stowage rack mockup is assembled from seven subassemblies directly around the support stand. The load path from the spacecraft mockup goes through the shoulder roll (T) drive and two outboard support legs. The upper part of the support stand acts as the docking probe. The entire system was made for easy disassembly, shipping, and reassembly. The servicing mechanism/module operating envelope shown is an outside bound based on extremes of travel considering both the side and base interface mechanisms. Reference dimensions for the major parts are also shown on the figure. Wiring from the junction box to the ETU goes directly up the support stand. Stowage rack status indicator wiring goes directly from the junction box to the stowage rack, while the status wiring to the spacecraft is routed along the floor, up an outboard support leg, and then over to the spacecraft. This avoids the need to run these wires through the shoulder roll (T) drive.

It was found convenient to lable the various ETU joints with letters. These designations are shown on Figure II-4. The length of the ETU arm segments are also shown.

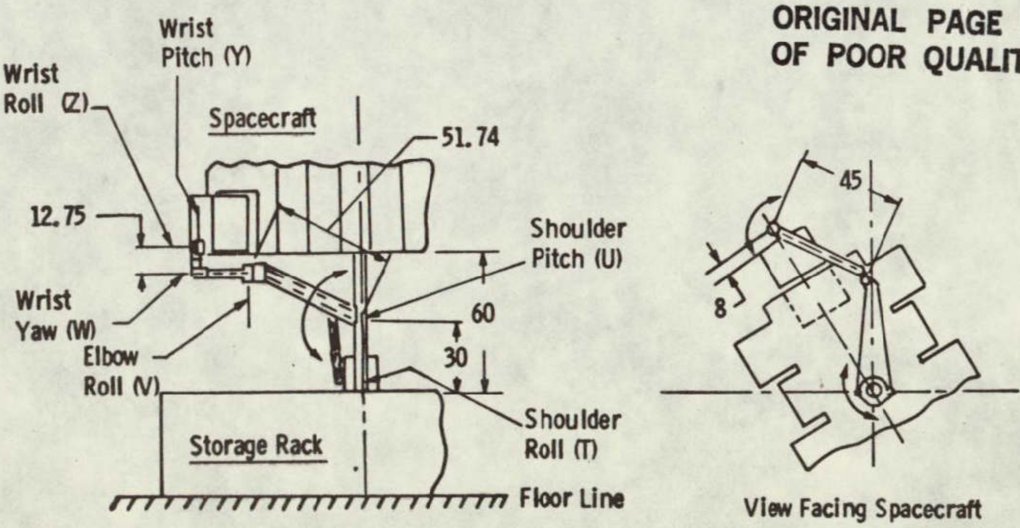


Figure II-4 Servicer System Joint Designations

The specifics of the ETU are discussed in Chapter III below and those of the SSDC are discussed in Chapter IV. The software is described in two references: *Servicer Simulation Software Requirements*, Rev. C, February 27, 1978, Martin Marietta, Denver; and *Servicer Simulation Software Design Document*, August 12, 1977, Martin Marietta, Denver. Copies of both these documents were provided to NASA-MSFC.

The spacecraft mockup is shown in Figure II-5 as set up at Martin Marietta. It is fabricated primarily of wood and cardboard with sufficient detailing to provide a reasonable representation of a generalized spacecraft. The docking axis has been offset so axial module exchange can take place at the maximum expected radius of 80 inches and radial module exchange can take place on the short end of the spacecraft. The third module loca-

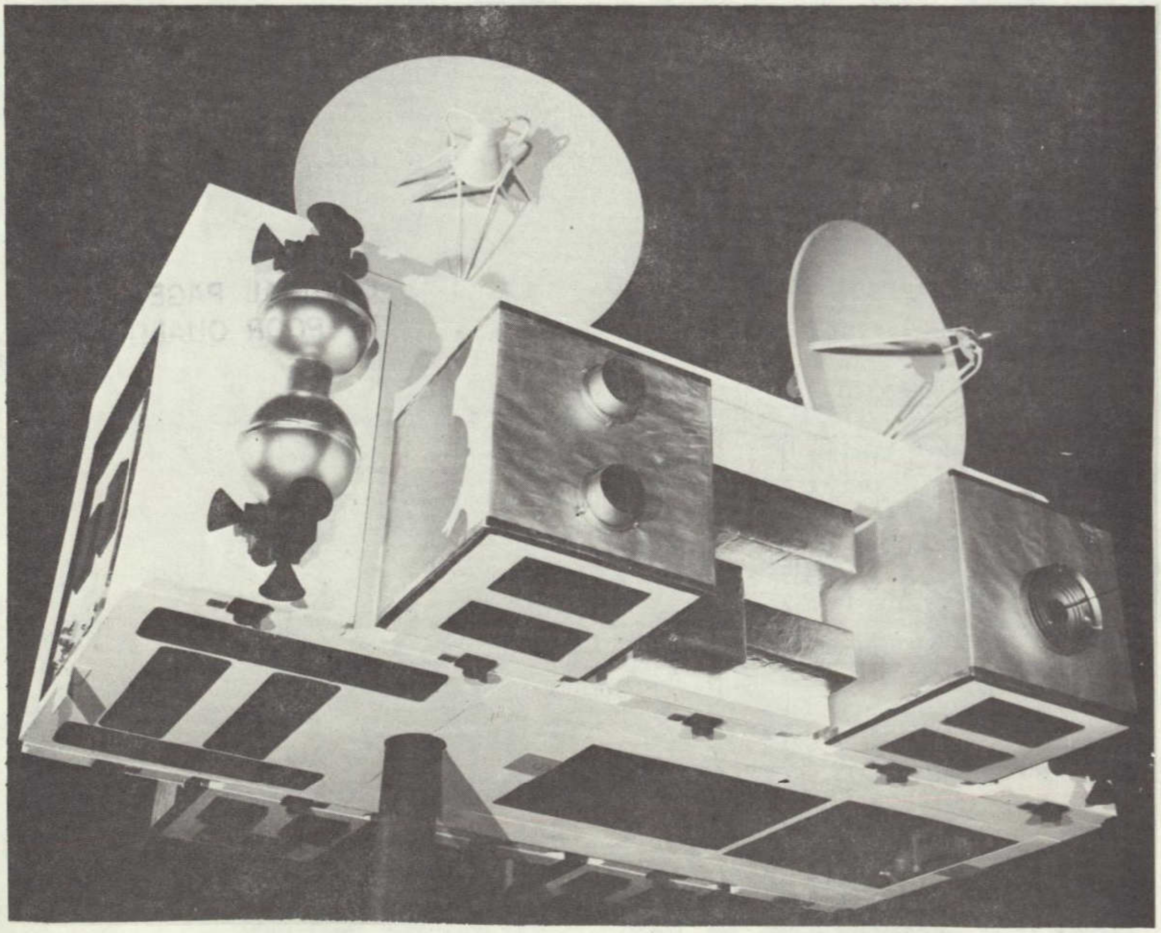


Figure II-5 Spacecraft Mockup

tion is also axial and was selected to be near the minimum radius of 20 inches. The module locations can handle either side or base interface mechanisms. When the interface mechanism type is changed, or when the location of an interface mechanism is changed, it is necessary to remove some of the exterior covers, move the mechanisms, check the electrical connections, and then replace the covers. While this approach takes some time, it minimizes the weight and cost of the spacecraft mockup.

The stowage rack mockup is shown in Figure II-6. It is also fabricated primarily of wood and cardboard to give a reasonable representation of the module stowage rack as designed for the flight version of the servicer and as described in Volume II. The far side of the stowage rack was cropped and the fourth truss was deleted to permit the total system to fit better

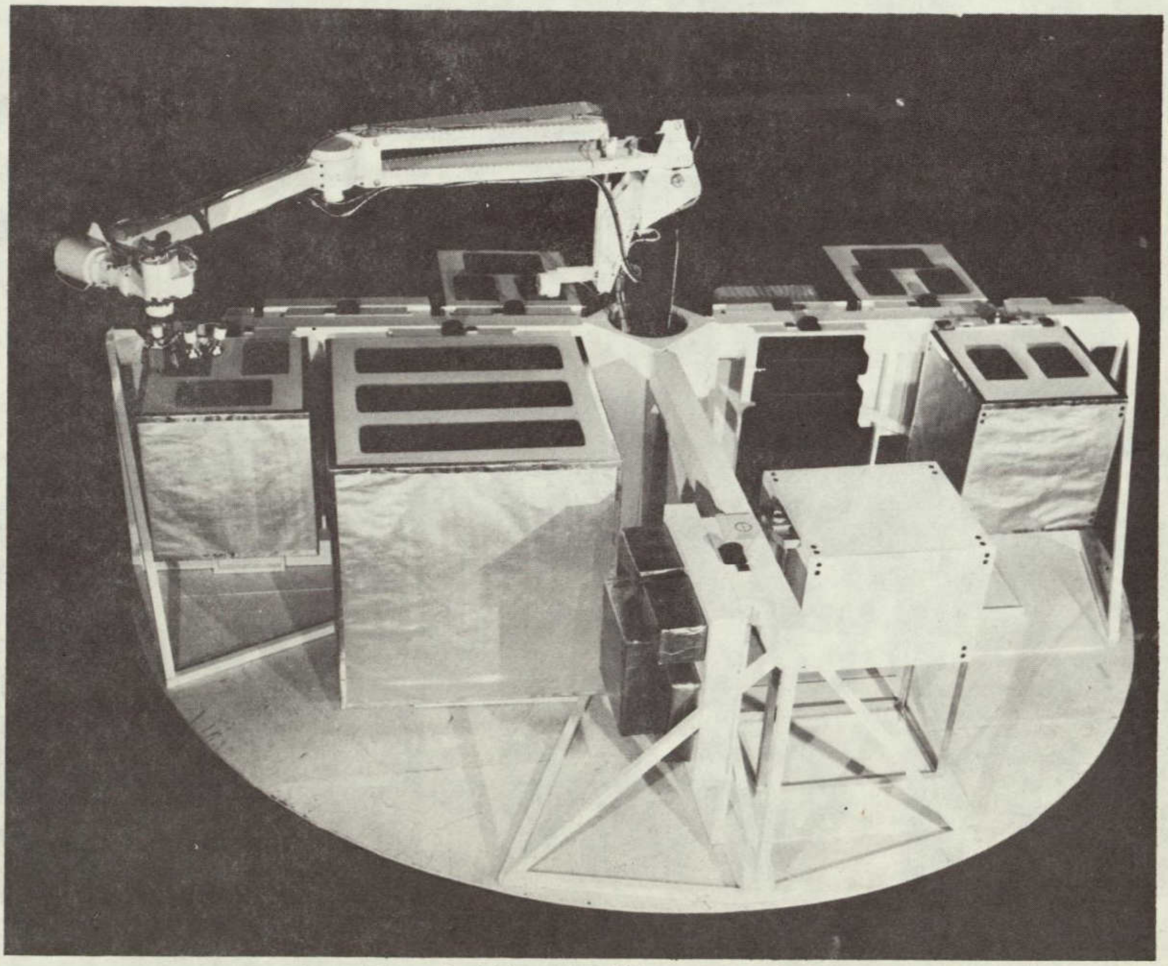
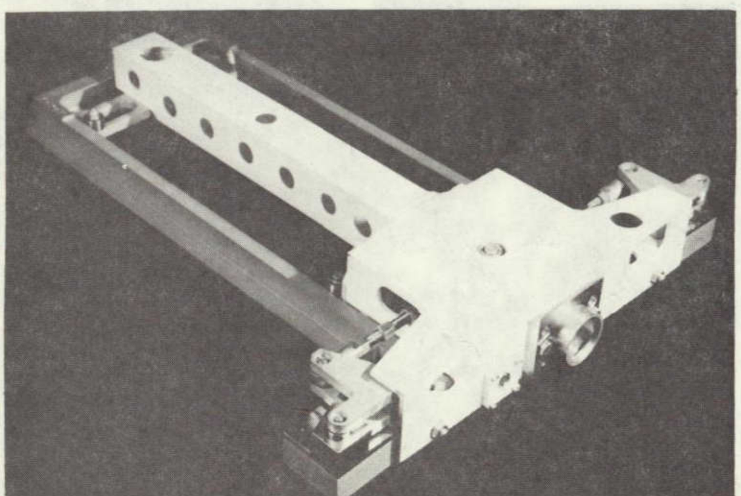


Figure II-6 Replacement Module Stowage Rack Mockup

in Room A122 and so it could be used with the motion generator during the January/February 1977 simulations. Twelve module representations were included to illustrate a range of sizes and shapes. The large module in the left hand quadrant is a 40-inch cube. The replaceable modules are shown in the right front quadrant. These modules can be placed anywhere in the right front quadrant of the stowage rack by merely moving them. No other setup or modification is required. Module locations should be marked so the modules can be returned to their locations should they be inadvertently moved. The module support structures are not fastened to either the stowage rack or spacecraft and a few inches of motion clearance have been provided. This will minimize the chance of damage should small inadvertent motions of the ETU occur.

Three sets of baseplate receptacles were provided for each style of interface mechanism. The sets consist of one each for axial exchange in the spacecraft, radial exchange in the spacecraft, and axial exchange in the stowage rack. The side interface mechanism is shown in Figure II-7 with and without a module representation. The module is a 24 inch cardboard cube that was configured for minimum weight. The side interface mechanism was designed and fabricated during an earlier contract phase.



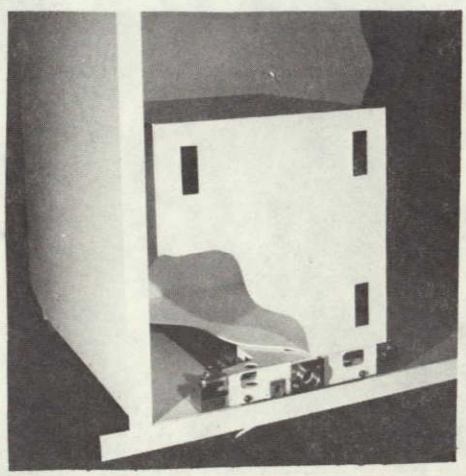


Figure II-7 Side Mounting Interface Mechanism

The base mounting interface mechanism is shown in Figure II-8 with and without a module representation. The module is a 18 x 24 x 26 inch foam core representation that was configured for minimum weight. The base interface mechanism is heavier and has a more adverse c.g. location than the side unit and thus requires higher motor torques to support and turn. The base interface mechanism was designed and fabricated during an earlier contract phase. It was modified during this contract phase to increase the module dimension to 18 inches and to relocate the latch drive interface so it would be compatible with the side unit. Compatibility was required because of the TV camera location with respect to the latch motor on the end effector. A brace was also added to transfer the outboard gear box weight loads back to the end effector attach point.

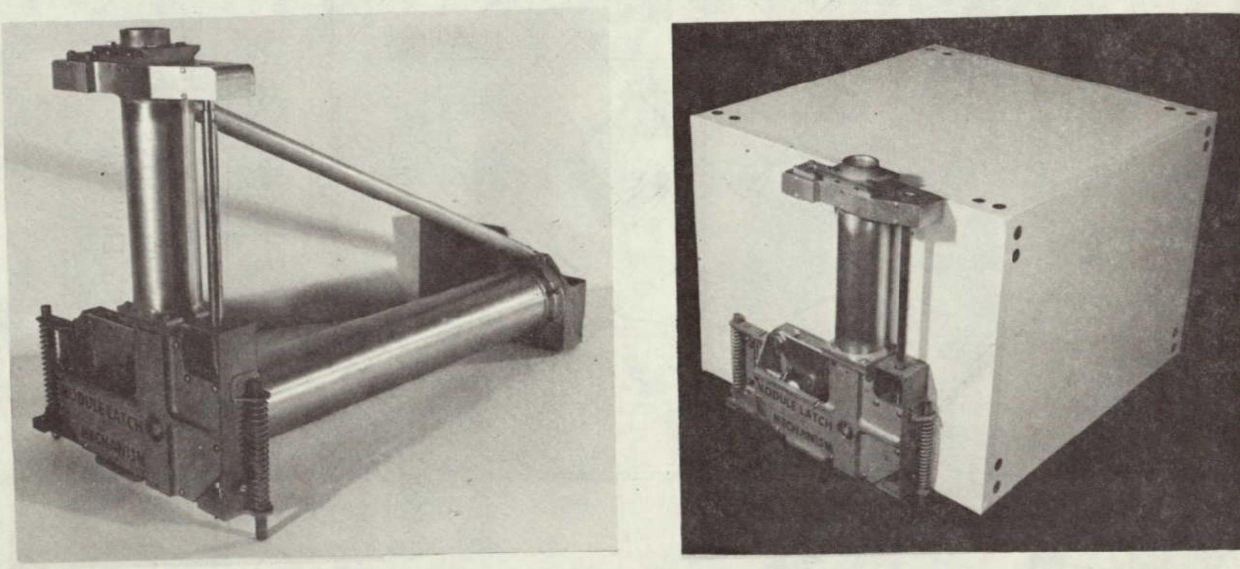


Figure II-8 Base Mounting Interface Mechanism

A layout of the one-g servicer demonstration system in Room A122 of Building 4487 at MSFC is shown in Figure II-9. The mockups and ETU have been located to one side of the room to maximize the viewing and working area. The spacecraft mockup orientation and active part of the stowage rack were selected to provide good sight lines for both visitors and the SSDC operator.

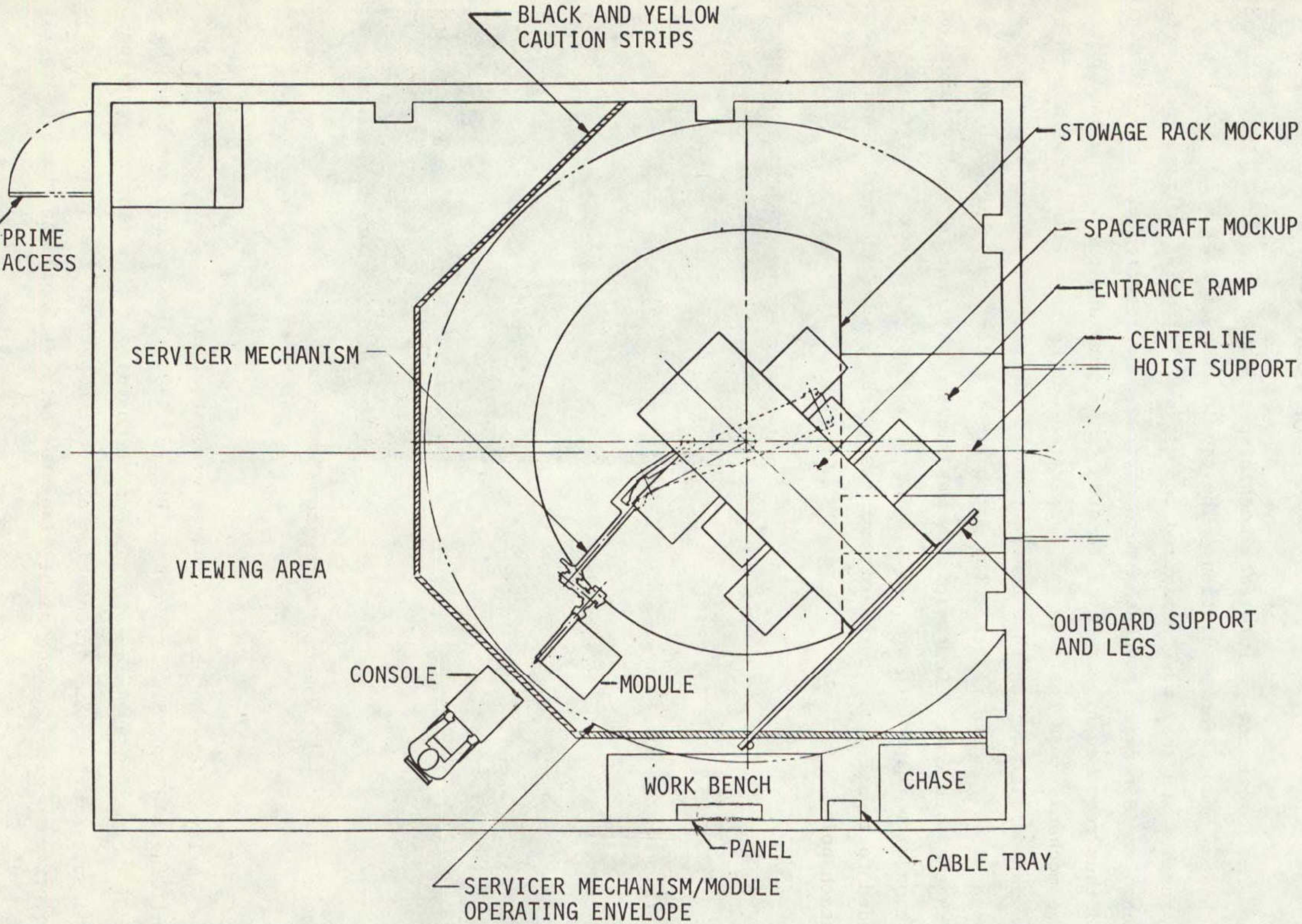


Figure II-9 One-G Servicer Demonstration Facility

The SSDC has been shown to one side midway between the mockups and the chase. The cables to the EC teleoperator laboratory and the SEL840A computer go through the cable tray. Caution provisions were made to protect visitors from module motions. The primary safety monitor is the SSDC operator. He has a switch which disconnects servo power from the motors and applies the joint brakes. Limit switches have been provided on all drives to disconnect motor power and apply the brake when a limit is entered. However, these limits cannot be simply designed to prevent interference between a module and the mockups or the back wall--*it is the responsibility of the SSDC operator to avoid any unplanned contact of moving and stationary parts.* He is to warn the servicer system operator of impending problems and when necessary to interrupt servo power using the servo power switch on the servo drive panel of the SSDC. A similar switch has been located on the servicer control panel for the system operator.

C. SERVICER SYSTEM DEMONSTRATION AT MARTIN MARIETTA

The objective of the demonstration at Martin Marietta-Denver was to verify that the ETU and the SSDC were capable of module exchanges and could perform servicer mechanism control in all three modes of control--supervisory, manual direct, and manual augmented--for both radial and axial module removal. The demonstration was to be functionally configured as closely as possible to that to be conducted at MSFC to maximize the validity of data transfer and probability of successful demonstrations at MSFC. A Martin Marietta PDP 1145 computer was used to simulate the computer commands to be later provided by the SEL840A computer. Martin Marietta hand controllers were used for the manual augmented control mode rather than MSFC equipment. All deliverable hardware was exercised in the demonstration and had been individually and collectively checked out first.

The demonstration goal was to show the capability of the deliverable equipment, a Martin Marietta computer, and peripheral equipment to exchange SRU mockup modules between the functional mockups of the spacecraft and

stowage rack. The ability to control the system in each of the three control modes was included. This review included a series of tests which demonstrated the ability, in the manual direct control mode, to acquire reference target areas on the total working surface of the axial and radial spacecraft and stowage rack faces. The first test goal was to demonstrate the integrated mechanism and control system required accuracy to guide the end effector probe into proper alignment with the interface mechanism drogue on these faces. The second test goal was to accomplish point-to-point SRU module exchange trajectories between the stowage rack and spacecraft, insert the SRU modules, energize the interface mechanism, and drive the SRU modules into the fully mated position.

The setup used in this demonstration is shown in Figure II-10. The

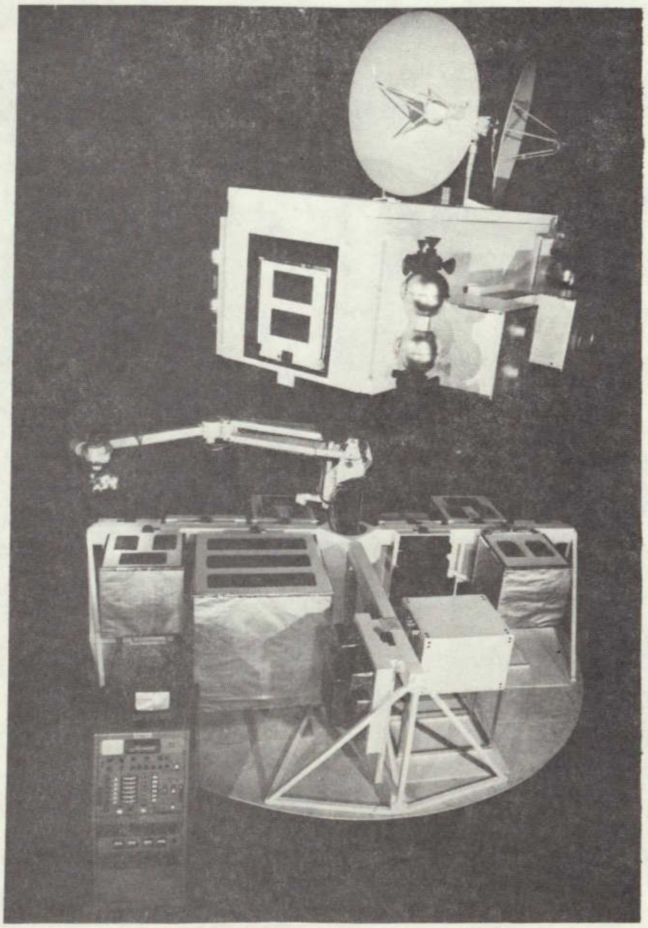


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Figure II-10 System Demonstration Setup at Martin Marietta

spacecraft and stowage rack mockups are shown along with the SSDC. The servicer mechanism has been positioned to the left rear so it is more visible. The control and display equipment used (servicer control panel, hand controllers, TV monitor, alphanumeric display and keyboard) are shown in Figure II-11.

Figure II-11 Servicer System Controls in Payload Specialist's Station

Significant demonstration results showed that all goals were met. The ability to reach all target areas on the spacecraft and stowage rack faces was demonstrated. Modules were successfully exchanged between the spacecraft and stowage rack in all three control modes. Both the side and base mounted interface mechanisms as well as radial and axial module exchange directions were demonstrated. The three side interface mechanism receptacles were set up in the stowage rack, the long radius axial location in the spacecraft, and the radial location in the spacecraft. The three base interface mechanism receptacles were set up in the stowage rack, the short radius axial location in the spacecraft, and the radial location in the spacecraft. Either the side or base interface mechanism could be used at the spacecraft radial location at any one time.

Each of the eight possible trajectories was demonstrated in the supervisory mode. The time available only permitted demonstration of four trajectories in the manual augmented mode and two in the manual direct mode. However, these were adequate to show that all trajectories could be used.

Portions of the demonstrations were repeated for various visitors led by a contingent from NASA-MSFC. Each person who accepted the opportunity to "fly" the system in the supervisory mode was able to excnange modules easily and successfully with a minimum of instruction. On completion of the tests and filming, the equipment was disassembled, packed, and shipped to MSFC.

D. SERVICER SYSTEM DEMONSTRATION AT MSFC

The servicer system demonstration at MSFC involved delivery of the equipments produced to the MSFC Electronics and Control Laboratory, and their setup and checkout in that facility. Integration support was provided for compatibility of the delivered equipment with the SEL 840 computer, the related MSFC-developed computer program, and teleoperator control center. Schematics, block diagrams, and other interface drawings as were necessary to integrate the equipment into the MSFC facility were provided.

On receipt of the equipment at MSFC it was unpacked, checked, assembled, and checked out. The checkout was performed in a step-by-step manner to ensure that all parts were working correctly. Figure II-12 shows the one-g servicer system set up in Room A122 of Building 4487. At that time the MSFC software was not complete so full demonstrations could not be conducted. However, module exchanges in the manual direct control mode were successfully accomplished. Final integration of the SEL 840A computer with the delivered equipment is underway at this writing. The setup was described and the mechanism was operated for a group of MSFC management personnel.

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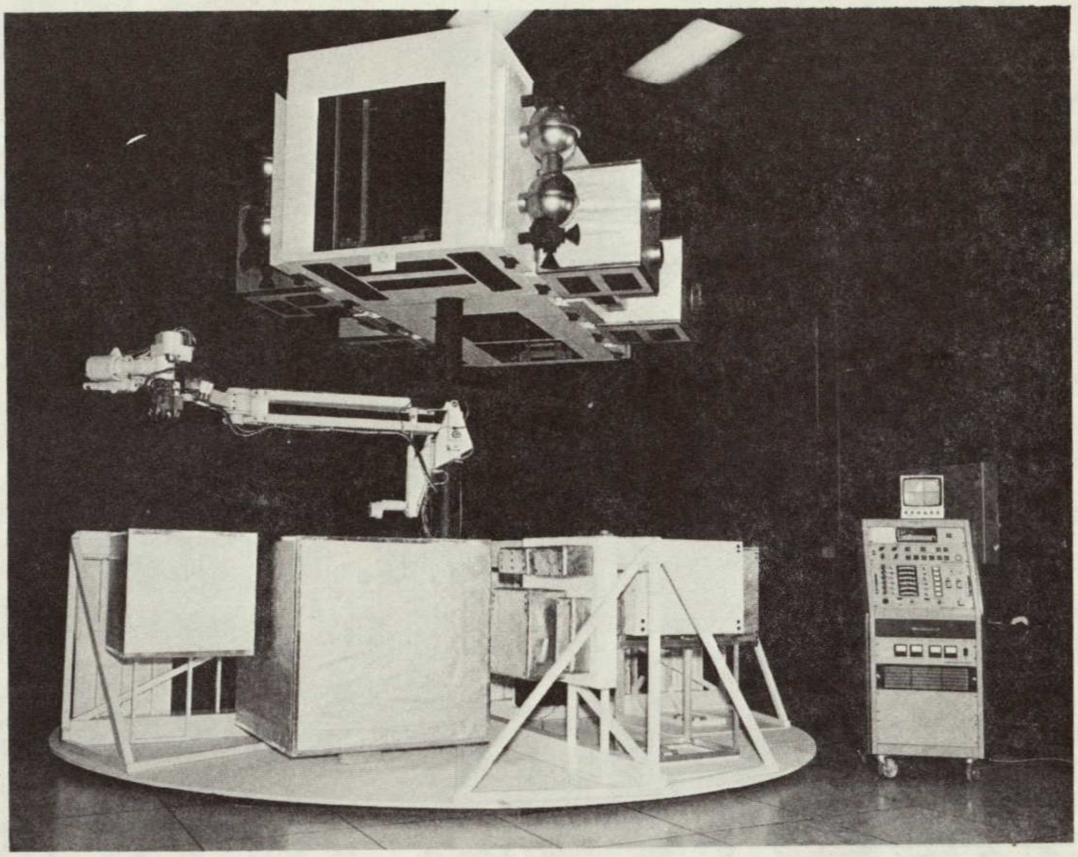

Figure II-12 System Demonstration Setup at MSFC

The Proto-Flight Manipulator Arm of NAS8-31487 has been installed in Room A122. This consolidates the newer MSFC manipulator systems in one area and simplifies their demonstration. It will also permit common use of electronics and simplify the experimentation to be conducted.

The MSFC manipulator test supervisor reported that the servicer system has been used a large number of times over the past three months and has worked perfectly with no maintenance being required.

III. ENGINEERING TEST UNIT

The one-g servicer mechanism engineering test unit (ETU) is a full scale, fully powered, counterbalanced six degree of freedom (DOF) device. It is servo-controlled, fully integrated into the control system, operates very smoothly, and is capable of going from axial to radial module removal with no special setup operations. It is a high quality, precision mechanism. Three of its drives have been adapted from the highly successful Proto-Flight Manipulator Arm (NAS8-31487) while the other three have been designed specifically for this application. The resulting unit is shown in Figure III-1. The mechanism itself is white, while the counterbalance and support structure is black.

The configuration was designed to accommodate servicing a one-tier spacecraft with module exchange being in the axial or radial directions. The servicer mechanism can remove modules in off-axis directions also. Modules can be located anywhere on the end surface of the spacecraft or stowage rack mockups, and both side and bottom mount interface mechanisms can be accommodated. The interface mechanism attachment points can be loca-

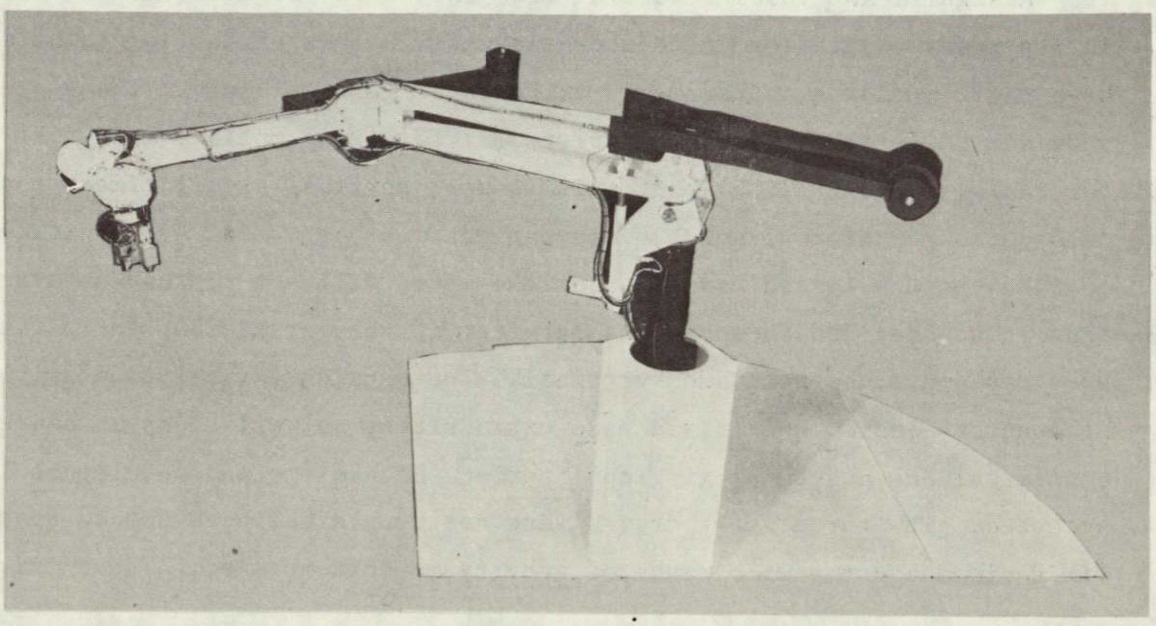

Figure III-1 Servicer Mechanism Engineering Test Unit

ted anywhere within a 20-inch to an 81-inch radius of the central docking axis. Modules can be located inboard or outboard of these radii if desired. Radial module removal can be effected for spacecraft or stowage rack radii up to 43 inches.

Two types of module flip can be used. One is inside the spacecraft and stowage rack envelope, the other is outside of the spacecraft and stowage rack envelope. The flip inside the envelope is more complicated and requires a coordinated motion between the four-bar linkage drive (U) and the wrist pitch drive (Y). The outside flip, which was used for the demonstration, merely puts the arm in its 90 percent extended position, and then the flip is performed with the wrist pitch drive (Y). The module is then relocated with the translation drive (U).

Each of the mechanism electromechanical drives incorporates a permanent magnet DC motor, a DC permanent magnet tachometer, a precision potentiometer, and a single limit switch (except for the wrist yaw drive, which uses two limit switches) with a cam to indicate the full range of joint travel. The backdriveable joints (T, V, Y, and Z) also have fail-safe brakes that hold the mechanism in position until energized.

A significant value resulting from use of the selected configuration is its ready adaptation to counterbalancing. Three of the joints normally have their motion axes parallel to the local vertical axis. These are shoulder roll, elbow roll, and wrist roll for axial motion, and wrist pitch for radial motion. If a joint axis is kept vertical at all times, then it need not be counterbalanced. The bearings must be strong and rigid enough to take the unbalanced moments, but the motor will not see any unbalance. Thus it was decided to mount the servicer in the arrangement shown with the shoulder and elbow roll axes vertical. The shoulder translation drive must be counterbalanced and it was made extra strong so variations in degree of counterbalance due to picking up interface mechanisms and modules could be accepted. The three wrist drives were not counterbalanced due to space limitations and the wide range of gravity moments applied. These drives were

designed with high capacities to handle the range of unbalanced moments expected.

The one-g servicer mechanism configuration has evolved throughout the more than three year lifetime of NAS8-30820 and reflects Martin Marietta experience prior to that time. The result is a useful configuration with excellent growth possibilities. The mechanism designs, especially with regard to the electromechanical drives, have also evolved over the years to result in strong, reliable, low backlash units that are light in weight. The result is a mechanism that was readily integrated with the control system to obtain a high quality one-g demonstration system.

A. PERFORMANCE CHARACTERISTICS

The ETU was designed to meet most of the requirements of the flight design. Some differences were necessary because of the one-g environment and to conserve study resources while obtaining an effective system. Performance characteristics of the ETU are listed in Table III-1. These characteristics are fully compatible with desired overall system performance. The tip force figure is exceeded when modules are not attached, cannot be obtained for some wrist orientations, but can be obtained for all planned module insertion/extraction conditions. The mechanism support post length was selected to put the shoulder pitch joint (U) axis 30 inches from the stowage rack and from the spacecraft. These distances are the same as for the flight unit.

While the performance characteristics of the ETU are significant, they can be extended as the on-orbit servicer demonstration facility evolves. Because the ETU is representative of the axial/near-radial flight unit configuration which is one of a family of five servicer configurations, the ETU can be extended to the other four modular forms. This implies changes in number and type of degrees of freedom, and number and length of arm segments. In the area of potential user's requirements it is possible to adapt the ETU to differences in type and size of interface mechanisms, module loca-

Table III-1 ETU Performance Characteristics

FULL SCALE
FULLY SERVO POWERED
COUNTERBALANCED
SIX DEGREES OF FREEDOM
SMOOTH, PRECISE OPERATION
AXIAL AND RADIAL MODULE REPLACEMENT
AXIAL/NEAR-RADIAL JOINT ORDER
TIP FORCE - 20 LBS
MAXIMUM OPERATING RADIUS
6.75 ft for Axial
3.5 ft for Radial
MODULE SIZE - 17 INCH CUBE TO 24 INCH CUBE (up to 40 in. cube for space design)
TIME TO REPLACE ONE MODULE - 10 MINUTES
SEGMENT LENGTHS
Upper arm, 51.74 inches
Lower arm, 45 inches
Extension, 12.5 inches
End effector, 8 inches
JOINT APPARENT BACKLASH LESS THAN 2 MIN ARC

tions in the spacecraft and stowage rack, spacecraft and stowage rack size, shape and configuration, module size and shape, and interface mechanism connectors--electrical, waveguide, and fluid. Note that electrical connectors are used on the interface mechanisms for status indication. As such they have provided a useful and reliable confirmation to the operator that the modules are firmly latched in place. A fluid disconnect, designed and fabricated by Fairchild Stratos for MSFC under Contract NAS8-32806, was incorporated and operated successfully in the Martin Marietta, Denver demonstrations. The involvement of this leak-proof fluid disconnect during the push/pull of module latching/unlatching demonstrated that the interface mechanism has the accuracy needed and generated sufficient force for mating and demating even when the disconnect was pressurized.

B. DESIGN APPROACH

The objective for the ETU design was to provide the best for the NASA considering the resources available. The three major criteria were to have the ETU representative of the flight unit, to avoid building in natural limits to growth, and to provide smooth operating joints. This last is particularly important for the shoulder and elbow joints because the arm segments magnify the errors of these joints and produce visual evidence of the errors in the form of end effector motions. However, the wrist joint errors are not magnified much at the end effector and not as seriously as the shoulder and elbow when the interface mechanism is attached.

When it was recognized that design time can be a significant part of total cost, it was decided to look at the Proto-Flight Manipulator Arm (P-FMA) (Contract NAS8-31487) joint designs for applicability. This work was done in the same group at Martin Marietta that designed the ETU and they had the detailed information to make a good evaluation of the P-FMA joint applicability. An examination of the available gearing costs data indicated that while the output gear costs are high, the incremental cost to go to the best quality was acceptable. The result was a decision to use high quality gears and output bearings in the shoulder and elbow roll drives. The shoulder translation drive was left slightly unbalanced so the backlash is always taken up and a less expensive drive could be used. By changing the direction of the unbalanced force when a module is being carried as opposed to the end effector only condition, a lower maximum magnitude of motor current results.

One area of difference from the flight unit was the decision to accept different torque and speed levels for the ETU joints if this would result in significant cost savings. These differences were later reduced by limiting joint rate commands and motor current and voltage levels in the electronics of the control system. In all cases, commercial parts were used unless higher pedigreed parts could be obtained for the same cost. The operating environment for the ETU is an air conditioned laboratory and it was not necessary to consider other environments.

The spacecraft and stowage rack mockups were fabricated as part of the January/February 1977 simulation activity. It was desired to use them with minimum modification. The ETU design adapted readily to the mockup constraints. Five sets of ETU drawings in the as-built form were provided to NASA-MSFC.

The Proto-Flight Manipulator Arm (NAS8-31487) is a seven degree of freedom, general purpose manipulator arm which was designed, fabricated, and delivered to the teleoperation laboratory of MSFC. It was designed to be flyable, yet was not subjected to the full NASA design review and qualification process generally associated with flight articles. There are two length versions of the arm--eight foot and four foot. The shoulder joints were designed to provide a 10 pound tip force in the eight foot configuration under all environmental conditions. The accuracy requirements are on the order of one part in 2,000 and the gearing errors measured less than two arc minutes. This performance is better than is required by the ETU.

An examination of the six drives on the ETU showed that three of them (shoulder translation, wrist yaw, and wrist roll) have configurations that are too different to attempt application of the P-FMA drives. The P-FMA does have a worm drive which might have been used for segment twist (P-FMA shoulder roll), but it is too large for the wrist yaw application. Fortunately, the two ETU drives where backlash and smoothness are critical could be considered for P-FMA joint application.

The factors considered are shown in Tables III-2 and -3. The need for high joint stiffness in the P-FMA resulted in very strong joints so they can accept the higher loads of the ETU in its controlled environment. The spacecraft mockup moments on the shoulder roll drive were minimized by adding two legs to the mockup. The difficulty was in the uncertainty in loads when the mockups are being reconfigured or when module locations are being changed and the fact that these moments must be carried through the shoulder roll (T) drive. The mockup legs also provide a safer situation when a person stands on the spacecraft mockup during its erection or modification.

Table III-2 Applicability of Proto-Flight Manipulator Arm (P-FMA) Joint Drive Designs

- THREE POSSIBILITIES -- SHOULDER ROLL (T), ELBOW ROLL (V), AND WRIST PITCH (Y)
  - Shoulder translation is ball screw drive
  - Wrist yaw is small worm drive
  - Wrist roll drive must surround end effector drive
- SHOULDER ROLL (T) CONSIDERATIONS
  - Support of the mechanism and counterbalance weight
  - Support of the spacecraft mockup weight and moment
  - Joint stiffness
  - Mounting configuration
  - P-FMA shoulder yaw drive was selected
- ELBOW ROLL (V) CONSIDERATIONS
  - Support of the outboard weight and counterbalance
  - Joint stiffness
  - Mounting configuration
  - P-FMA shoulder pitch drive was selected
- WRIST PITCH (Y) CONSIDERATIONS
  - Support of outboard weight
  - Unbalanced moments
  - Joint stiffness
  - Mounting configuration
  - P-FMA elbow pitch drive was selected

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In addition to the joint drive applicability considerations, torque and speed are also of interest. The torque requirements for the flight unit drive were derived from commonality considerations across all five servicer modular configurations. First each servicing modular configuration was examined to determine the torque requirements separately due to tip force and module acceleration. These were determined over the applicable range of arm configurations including module extended and then module tucked in adjacent to the forearm, and then a commonality assessment was made across all joints to minimize the total number of joints required. The result was that the requirements were larger than needed for specific arm configurations. These data for the ETU shoulder and elbow roll and wrist pitch drives are tabulated.

Table III-3 Torque and Speed Considerations - T, V, and Y Drives

TORQUE CONSIDERATIONS (ft-lbs)	SHOULDER ROLL (T)	ELBOW ROLL (V)	WRIST PITCH (Y)
Flight Configuration	225	200	30
Axial/Near-Radial Tip Force	191	162	--
Axial/Near-Radial Acceleration (high)	191	182	23.4
P-FMA	SHOULDER PITCH OR YAW DRIVE	ELBOW PITCH DRIVE	
Motor Stall Torque	160	88	
Motor Torque at 0.1 rad/sec	128	--	
Motor Torque at 0.14 rad/sec	115	--	
Motor Torque at 0.21 rad/sec	--	59.3	
Allowable Gearing Load	139	149	
Allowable Bearing Load, static	104	47	
Allowable Bearing Load, dynamic	235	126	

CONCLUSION -- Torque is low, but acceptable.

SPEED CONSIDERATIONS (rad/sec)

Shoulder Roll (T) - 0.1

Elbow Roll (V) - 0.14

Wrist Pitch (Y) - 0.21

P-FMA Drives at 20% Load--Shoulder = 0.4, Elbow = 0.52

CONCLUSION -- Limit joint velocities in control system

As it is planned to use only lightweight modules with respect to the ETU, it is not necessary to satisfy the module acceleration requirements.

The torque requirements shown for the flight configuration to satisfy the 20 lb tip force requirement are higher than are needed for the ETU because of the shorter ETU segment lengths. The flight configuration torques should be ratioed down by a factor of 0.61 for the same tip force in the ETU. Consideration of these points, the specific numbers presented in Table III-3, and the cost of redesign leads to the conclusion that while the Proto-Flight Manipulator Arm (P-FMA) shoulder pitch and yaw drive torques are slightly low, they are acceptable.

The P-FMA elbow pitch drive far exceeds the wrist pitch torque requirements of the flight unit. However, the ETU requirements are set by the unbalanced moments due to handling the interface mechanisms and mocked up

modules. During a module flip with the base interface mechanism up to 78 percent of the P-FMA elbow pitch drive capability will be used. During module insertion or extraction, at most 36 percent is rquired. Thus the P-FMA elbow pitch drive will be satisfactory for the ETU wrist pitch drive

With regard to joint speed, the P-FMA drives are much faster than the ETU requirements. This means that the P-FMA drives can be used, but that the joint maximum velocities must be limited in the control system so the module exchange times will be representative of the flight unit characteristics.

It was decided to not counterbalance the wrist drives. It is usually possible to reduce the torque requirements by counterbalancing out part of the load. A wrist counterbalance system would have--1) reduced the space available between the spacecraft and stowage rack for module removal, 2) increased the total weight at the wrist and thus the elbow and shoulder counterbalance weights, and 3) would probably have reduced wrist joint travel because of increased interferences.

Selection of the electromechanical components for the ETU followed the same general rules as were used for the flight version (see Volume II, Chapter VI). The electromechanical components used in the various drives along with some of their important characteristics are listed in Table III-4. Note that potentiometers are used on all six axes. This is possible because of--1) the shorter arm lengths, 2) the stable environment, and 3) the ability to calibrate out all consistent errors.

C. DESCRIPTION

The overall configuration of the engineering test unit is similar to that for the flight unit design and is shown in Figure III-2. It has six degrees of freedom and the arm lengths appropriate for axial and radial module removal. The individual drives are discussed below. The forearm is a commercially-available thickness of four-inch-square aluminum tubing. The

Table III-4 ETU Electromechanical Component Summary

			MOTOR				POSITION SENSOR			RATE SENSOR			BRAKE	
JOINT DESIGNATOR	DRIVE TYPE	MOTOR TO OUTPUT GEAR RATIO	TYPE	VENDOR/ PART NUMBER	STALL TORQUE	NO-LOAD SPEED (rad/sec)	TYPE	VENDOR/ PART NUMBER	LINEARITY	TYPE	VENDOR/ PART NUMBER	MAX SPEED (rad/ sec)	VENDOR/ PART NUMBER	TORQUE (ft-lb)
Shoulder Roll (T)	Dual Path Internal Gear	109.61	DC Torque Motor	Inland T-4412	1.5 ft-lb	55	1 Turn Pot	CIC 155	.075%	DC Tach Gen.	Inland TG 1312-A	63	Delavan BFR-20-24	1.2
Shoulder Pitch (U)	Ball Screw	--	DC Perm. Magnet	Duff Norton MPD-6405	500 lbs linear force = 375 ft-lbs	68 in./min equiv. to .12 rad/sec	1 Turn Pot	CIC 205	.05%	DC Tach Gen.	Inland TG 2139-A	77	N/A	N/A
Elbow Roll (V)	Dual Path Internal Gear	109.61	DC Torque Motor	Inland T-4412	1.5 ft-lb	55	1 Turn Pot	CIC 155	.075%	DC Tach Gen.	Inland TG 1312-A	63	Delavan BFR-20-24	1.2
Wrist Yaw (W)	Planetary and Worm Gear	50.0 (worm only)	Gear Motor	Globe Ind. 102A162 (BD-11) Gear Head Ratio = 117:1	7.2 ft-lb, (85% eff)	6.9	1 Turn Pot	CIC 105	.1%	DC Tach Gen.	Inland TG 1312-A	63	N/A	N/A
Wrist Pitch (Y)	Dual Path Internal Gear	103.09	DC Torque Motor	Inland T-2955-D	.85 lb-ft	67	1 Turn Pot	CIC 205	.05%	DC Tach Gen.	Inland TG 1312-A	63	Delavan BFR-20-24	1.2
Wrist Roll (Z)	External Spur Gear	35.56	DC Torque Motor	Inland T-2406A	2.5 lb-ft	84 derated to 66	10 Turn Pot	CIC 7814	.05%	DC Tach Gen.	Inland TG 2139-A	77	Delavan BFR-20-24 Ratio to Motor = 1	1.2
End Effector Jaws	Ball Screw and Planetary	81	DC High Speed	Globe Ind. 5A505-7	7.0 in.-oz. (torque eff = 50.4%)	1,456	Micro-switch	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Interface Mechanism	Planetary	148	DC High Speed	Globe Ind. 5A509-7	7.0 in.-oz. (torque eff = 50.4%)	1,456	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

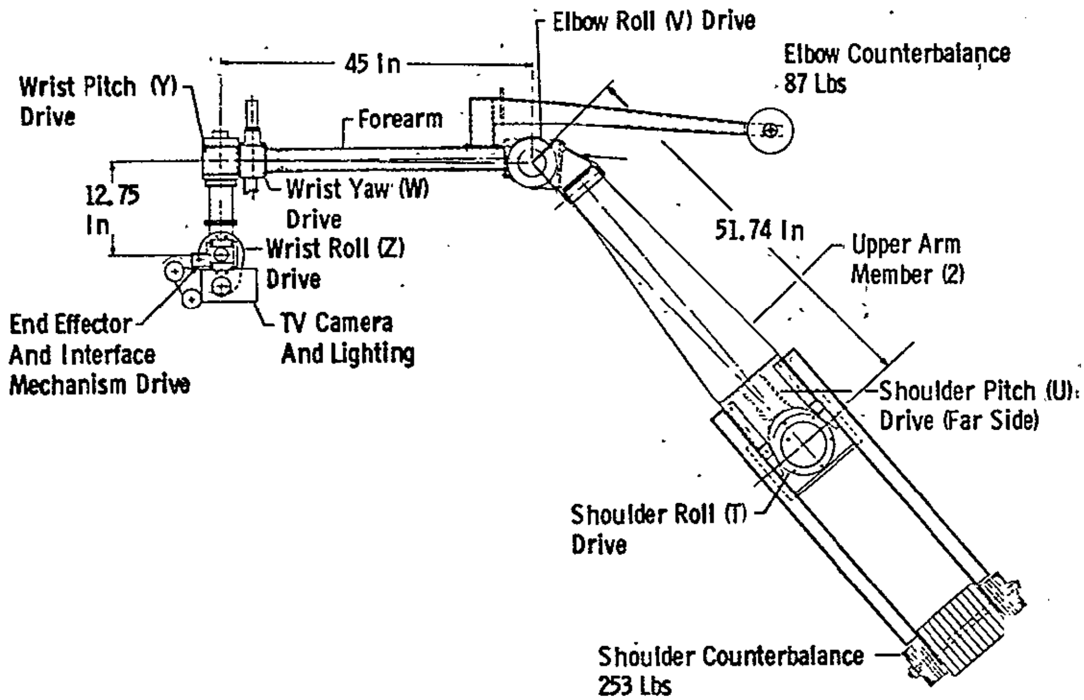

Figure III-2 ETU-Mechanism Configuration

overall arm length of ten feet includes the end effector length but not the mounting distance from the shoulder pitch drive axis to the face of the stowage rack. The four bar linkage, or translation members, were built up from machined end fittings, side channels, and facing plates. Each member is a riveted assembly with appropriate stiffeners. The original concept used open construction to simplify the assembly operations. However, a strain analysis showed that the members could be stiffened significantly if the boxes were closed, so this was done. The critical stiffness configuration is with the lower arm at 90 degrees to the translation members so the translation members are being twisted about their longitudinal axes. The closed boxes and the member spacing selected provided the necessary stiffness.

The shoulder roll drive shown in Figure III-3 was adapted from the P-FMA shoulder yaw drive. It mounts to the 81-in. long lower support stand which is made from 6.63-in. diameter steel pipe. The bottom of the lower support stand is a large weldment to provide a stiff interface with the floor. The

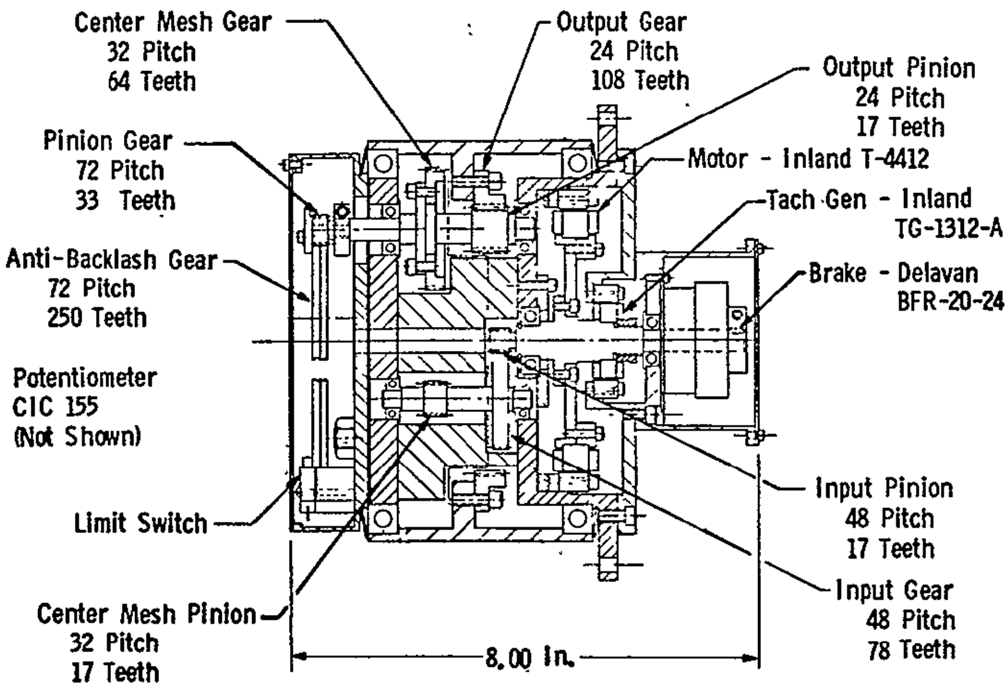

Figure III-3 Shoulder Roll Drive

upper support stand is an aluminum tube which supports the spacecraft 60 inches above the stowage rack. The two parts of the support stand are bolted together through the T drive gear plates. Large diameter, small cross section output bearings were used to provide a high level of structural stiffness.

The permanent magnet DC torque motor is shown on the center shaft along with a tachometer generator and a fail-safe brake. The overall drive ratio of 109.6 to 1 is obtained in three steps in a dual path approach. The center mesh gears are adjustable on their shafts and were used to remove much of the drive backlash. After adjustment, the center gears were pinned to their shafts. This straight spur gear construction is backdriveable at a low torque level. Seals or covers were provided for all bearings.

The position indicator selected is a single turn plastic film potentiometer and is driven through an antibacklash gear. The potentiometer drive gearing provides over a full revolution of travel of the joint.

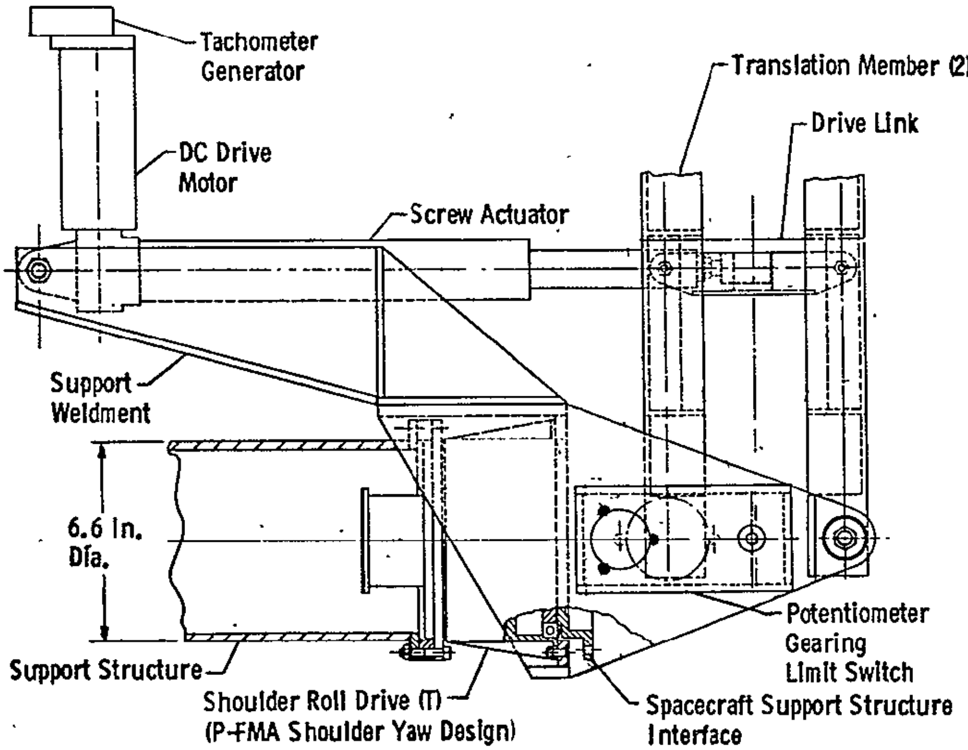

Figure III-4 ETU-Shoulder Pitch Drive (U)

The shoulder pitch drive (U), shown in Figure III-4, is patterned after the flight unit approach with a number of modifications to decrease cost. The shoulder roll drive (T) is bolted directly to the support structure. The output of the roll drive bolts directly to a new weldment. This weldment provides support for the translation members and the shoulder pitch drive. The pitch drive takes the form of a commercially available Duff-Norton Company screw actuator. This actuator has the proper force, stroke, speed, and strength capabilities. It incorporates a 0.044 horsepower, 12 volt DC motor. The automatic mechanical brake which is normally assembled in this unit was removed to reduce motor starting current. The system counterbalance was adjusted so the drive always operates on one side of the backlash region when a module is being inserted or withdrawn.

The position sensor and the limit switch cam could not be easily integrated into the screw actuator so they are geared directly to the lower translation member. This bypasses the screwjack backlash. The position indicator is a single turn plastic film potentiometer geared up through an antibacklash gear so full U joint travel produces almost full travel of the potentiometer. Initially, the tachometer generator was geared up from the potentiometer drive. However, this was found to be unsatisfactory due to the large backlash between the motor and the tachometer. The tachometer was relocated to be driven through one stage of gear reduction from the motor. This resulted in a stable system and satisfactory operation.

Use of the two translation members in a parallelogram configuration results in the forearm of the servicer being kept parallel to the front of the stowage rack. This simplifies the hazard avoidance problem. However, as the shoulder pitch drive alone is operated, the end effector moves along an arc instead of along a straight line. This is not too important when the end effector alone is being moved, but it is important when a module is being removed from the interface mechanism receptacle (guides). For the module to move in a straight line parallel to the docking axis, the shoulder pitch, shoulder roll, elbow roll, and wrist roll joints must move in synchronism. When the module is in the guides and the shoulder pitch joint is providing the basic motion, then the other three joints will back-drive and should automatically move in the proper synchronism. Note that the supervisory and the manual-augmented control systems generate the proper control signals so these joints will move in synchronism.

The elbow roll drive (V), shown in Figure III-5, started with the detail design of the proto-flight manipulator arm (P-FMA) shoulder pitch joint. Minimum changes were made for the ETU application. The P-FMA resolver was deleted and replaced by a single turn plastic film potentiometer. Design of the adapters from the P-FMA housings to the arm segments was straightforward and the adapters were made from commercial aluminum plate and angles. The outer arm segment is a stock size (4 inches) square aluminum tube with plates welded on the ends.

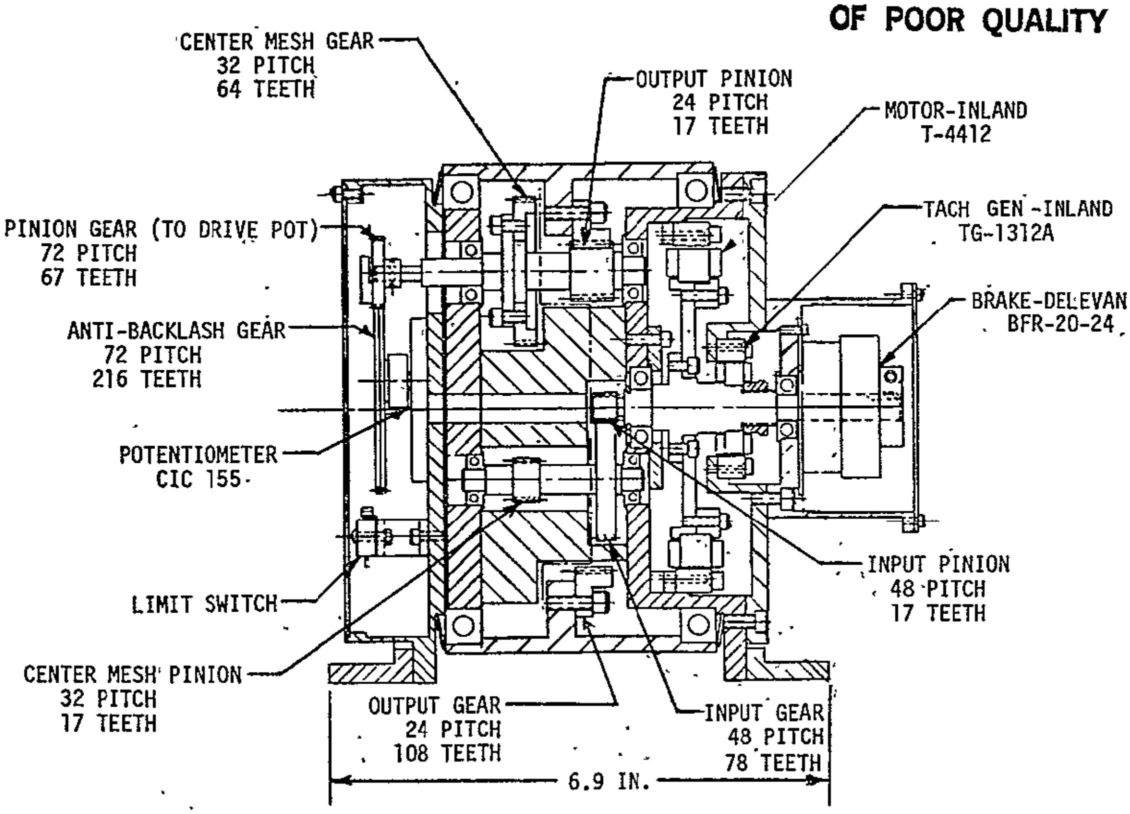

Figure III-5. ETU-Elbow Roll Drive (V)

The elbow roll drive is an internal gear dual path drive. It is mated to the parallelogram translation linkage through an angle fitting. The joint centerline is mounted offset from the centerlines of the translation members and the outer arm segment so these arms may be folded back toward each other with a minimum of interference.

The drive is powered by a permanent magnet DC torque motor mounted on the input shaft. The input shaft pinion drives a dual mesh, three-stage gear reduction. The final gear stage terminates with the internal gear which is fixed to and drives the outer housing. The tachometer (rate sensor) is mounted to the input shaft, giving the maximum voltage level for rotational speed. The fail-safe brake is also mounted on the input shaft which requires the minimum torque, and therefore power to restrain the drive if motor power were interrupted. The overall drive ratio of 109.6 to 1 is obtained in three

steps. The center mesh gears are made adjustable as for the shoulder roll drive. This straight spur gear construction is backdriveable at a low torque level. Seals or covers are provided for all bearings.

The potentiometer (position sensor) is driven through an antibacklash gear from the third shaft. This reduces the position error due to gear backlash in the output gear stage. The potentiometer drive gearing allows full joint motion for almost full potentiometer motion. A single limit switch is provided as an indicator that the drive has reached its maximum travel.

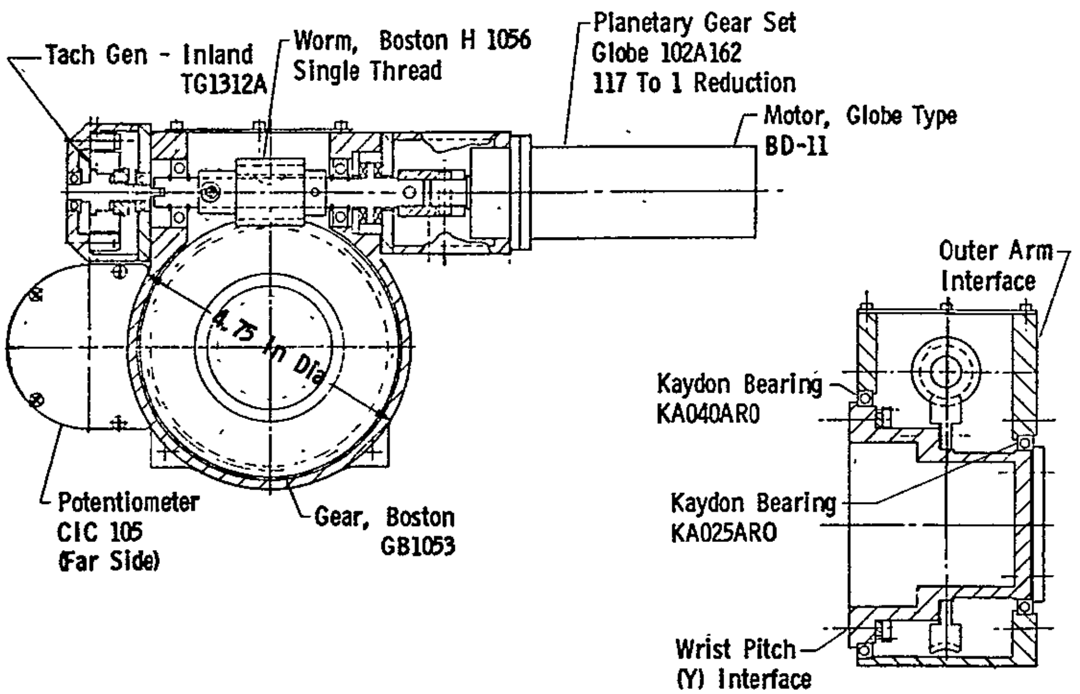

Figure III-6 ETU-Wrist Yaw Drive (W)

The wrist yaw drive (W), shown in Figure III-6, is an adaptation of the flight unit configuration. It is a simple worm drive with the axis of rotation being parallel to the outer arm segment long axis. The wrist yaw drive is mounted outboard near the wrist to reduce the loading on the drive output bearings and thus the weight of the drive. This drive is larger and stronger than the flight unit drive because it must handle the base mounting

interface mechanism in one-g. It is difficult to counterbalance the un-balanced wrist and interface mechanism torques without sacrificing the length of modules that can be handled.

The torque limit spring arrangement of the flight unit has not been included. The function is essentially provided by the interface mechanism receptacle support structures in the stowage rack and spacecraft mockups. The figure shows how the feedback potentiometer, the tachometer generator, and their drive gearing are mounted. A brake is not necessary as the worm gear is not backdriveable.

The purpose of the W drive is to position the wrist pitch drive so it can turn the modules end for end and also help in radial module exchange. The W drive is thus basically an indexing and not a servo drive. It is to drive at a constant rate during the Y drive repositioning and thus a tachometer generator has been provided. The tachometer is also used for loop stability. A 50:1 worm gear ratio is used along with a gearhead on the DC permanent magnet motor to provide the necessary slow speed from a small high-speed motor. A single turn plastic film potentiometer is used to provide an indication of which index point the joint is at as well as the position feedback information to the control system.

The wrist pitch drive (Y), shown in Figure III-7, is the third of the proto-flight manipulator arm internal gear-dual path drives. Its outer housing mounts directly to the wrist yaw drive and the gearing support structure supports the short third arm segment leading to the wrist roll drive and end effector. The wrist pitch drive is functionally and mechanically very similar to the elbow roll drive discussed above. The input shaft supports the permanent magnet DC torque motor, the tachometer generator, and the fail-safe brake. The overall drive ratio is 103 to 1 and is obtained in three steps. Backlash removal is provided by center gear adjustment and the joint is backdriveable.

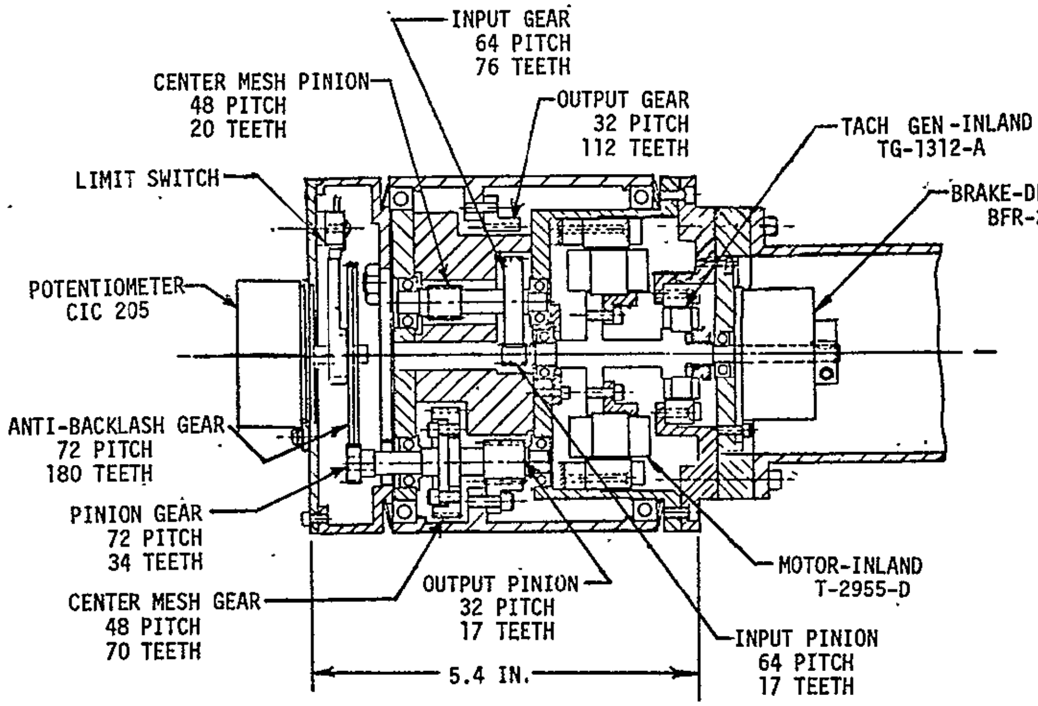

Figure III-7 Wrist Pitch Drive (Y)

The Y drive has a high torque level to be able to handle the unbalance moments due to the interface mechanisms and module mockups. The module fli trajectory is the most demanding. Module insertion/extraction requires les than half the torque required during the flip.

A single turn plastic film potentiometer is used for position sensing and is driven through an antibacklash gear to reduce the effect of output gear stage backlash. The gear ratio has been selected to give slightly les than one revolution of the potentiometer for a full revolution of the drive

The wrist roll drive (Z), shown in Figure III-8, is an adaptation of t flight unit configuration. It was configured to accept the end effector (E that was delivered on the first IOSS. The EE was modified slightly to provide a better interface with the wrist roll drive. The wrist roll gearing and its housing were configured to a simpler arrangement that was less expensive to fabricate. One result is that the Z drive is somewhat long-

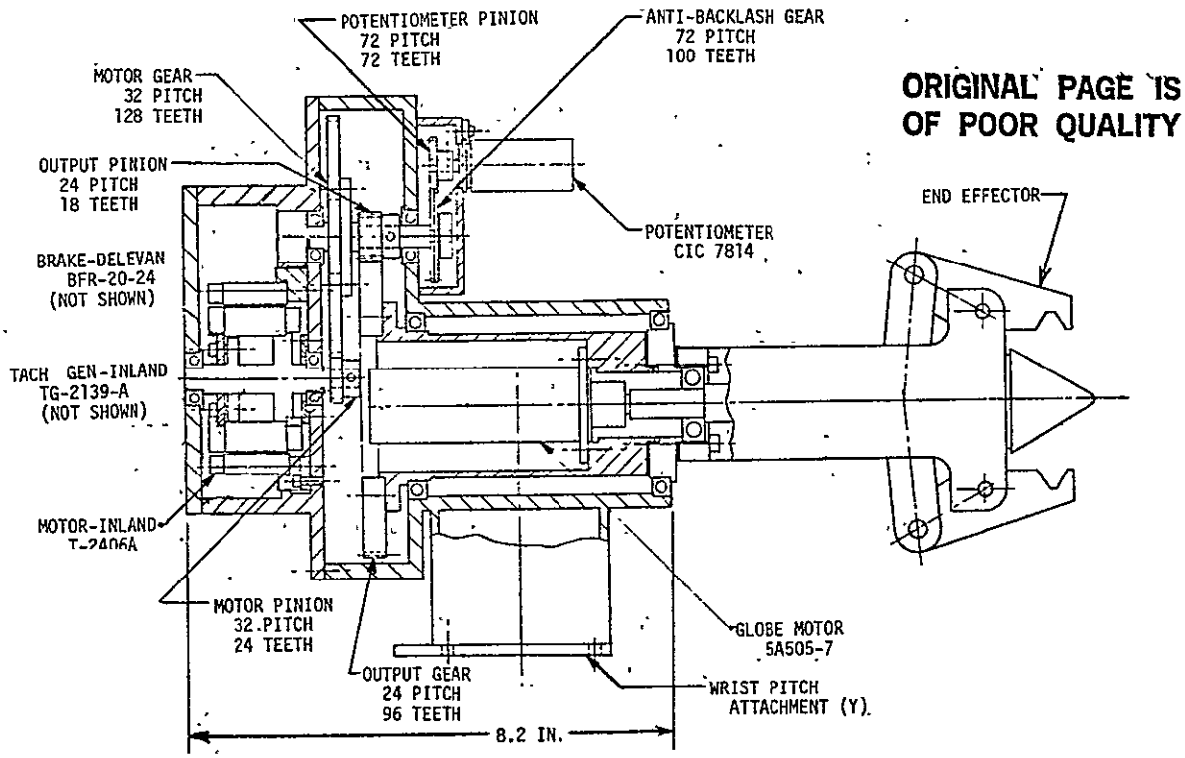

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Figure III-8 ETU-Wrist Roll Drive (Z)

er and the centerline of the forearm is a little farther from the end effector than is the case for the flight design. The effect of these longer dimensions is that the space between the spacecraft and stowage rack will not be used as efficiently. This means that is not possible to flip 40-inch cube modules within the space between the stowage rack and spacecraft. While the clearance for a 40-inch module is a little small, it should be maneuverable between the spacecraft and stowage rack and then flipped outside. The outside flip is the primary mode with the inside flip only being applicable to servicing within the Orbiter cargo bay.

The wrist roll drive design starts with the cylindrical outer form of the end effector which could be readily mounted in large diameter, small cross section bearings as is desired. The drive then took the form of a large gear mounted on the end effector and driven through a further gear re-

duction from the motor shaft. Other drive elements--brake and tachometer generator--are on their own shaft which is geared through an idler at 1 to 1 to the motor shaft. The ten turn, plastic film potentiometer is geared up from the output shaft through an antibacklash gear in the second mesh. Note that over 360 degrees of travel are provided in the wrist roll drive so any module can be positioned in any orientation on the spacecraft or stowage rack.

The end effector concept is an extension of our prior work on general purpose manipulators and is designed to mate with either of the two interface mechanisms. It accomplishes two things--1) it attaches the servicer mechanism to the module; and 2) it operates the latching mechanism. End effector attachment is accomplished by two closing jaws grasping a rectangle-shaped baseplate grip. The closing force is supplied by a motor-driven ball screw drive. This drive applies a low initial closing force when radial alignment is taking place and a very high final closing force when module handling is taking place. This high force occurs because the jaw links are approaching an overcenter position with respect to the ball screw carriage.

The interface mechanism latch drive mechanism (not shown) is an integral part of the end effector attach drive. It is operated by an electric motor through a gear head. The motor and gear train are designed to produce an operating torque of 8 in.-lbs with a stall torque of 33 in.-lbs. Both the end effector and interface mechanism latch drives are those of the first IOSS.

Installation of the TV camera and end effector lights are shown in Figure III-9. The camera is a General Electric 4TN2000A1 side lens solid state video camera which uses a charge injection device imager. The sensing region is 244 x 188 pixels and the camera is fully compatible with a standard monitor. The camera is fitted with an auto-iris lens which changes its light admitting characteristics to keep the output video at a useable level. As the camera gets closer to the target, the reflected light gets stronger and the lens iris closes down. This in turn increases the depth of field and permits operation over the full target range with one focus setting. The TV

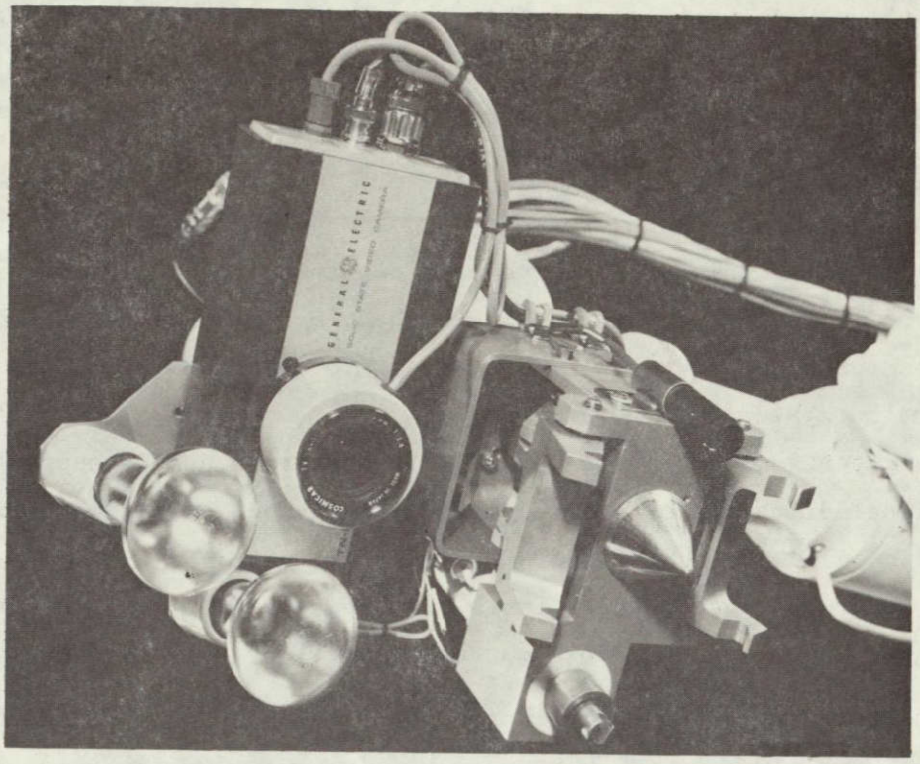


Figure III-9 TV Camera and End Effector Lighting

camera has a separate power supply box which is remotely located near the U drive to minimize counterbalance weights.

Two porcelain sockets have been provided for the end effector lights. The recommended bulbs are the 30 watt, built-in reflector, R20 type. The design will accept up to size R30 at 75 watts. The R20 bulbs only come in the flood pattern, while the R30 bulbs can be obtained in either spot or flood types. It is possible to study the effect of various light levels on the camera and control system.

The ETU counterbalance system is shown in Figure III-2. Note that no wrist counterbalancing has been provided. The purpose of the elbow counterbalance is to bring the center of gravity of all elements outboard of the elbow roll drive close to this V drive axis. In this way the variation in unbalance as seen by the shoulder pitch (U) drive will be less. The

purpose of the shoulder counterbalance is to bring the average unbalance torque seen by the U joint to zero. The elbow and shoulder counterweights were experimentally determined to minimize total counterbalance weight while minimizing the largest unbalanced torque on the U drive. Further considerations are presented in Section IV.C.

The counterbalance weights are segmented and can be added or removed in increments. Use of this property permits counterbalancing the mechanism, with or without the interface mechanism attached, more exactly in selected configurations for specific tests. *All changes to the counterbalanced condition should be carefully planned and analyzed before implementation.* After implementation, tests should be conducted with the arm manually supported as the individual drive brakes are released. Operations at minimum drive voltages, and running in each direction at the same voltage, will demonstrate an effective counterbalance. These tests must be repeated over the range of elbow angles to determine the elbow counterbalance.

A weight statement for the ETU is shown in Table III-5. The counter-

Table III-5 Engineering Test Unit--Weight Summary

	lbs	lbs
T Drive	21.2	
U Drive and 4-Bar Linkage Assembly	82	
V Drive and Forearm	26.2	
W Drive	12	
Y Drive	15	
Z Drive and End Effector	22.6	
TV Camera and Lights	6	
		185
Shoulder Counterbalance and Support	283	
Elbow Counterbalance and Support	94	
		377
TOTAL		562

balance and support weights are those installed when the ETU was tested in Denver. While the dual path drive weights are reasonable for flight units of the same torque capacity, the wrist drives have a larger torque capacity than might be used for a flight unit. The other drives are heavier than comparable flight units would be.

The ETU wiring harness was designed for ground use in that no attempt was made to minimize weight or provide extreme environment resistance. Separate cables are used for power and signal to reduce possible EMI. These cables are continuous from the control system junction box to the Z drive/end effector with branches off to each drive along the way. Connectors are provided at each drive and pin/socket splices within each drive to aid in assembly and disassembly. The motor and potentiometer leads are shielded while coaxial cable is used on the tachometer generator signals. Service loops are used to bring the cables across the movable joints. The wires are loosely bundled in the service loops to reduce stiffness and torque effects. Case ground straps are provided across each joint to protect against bearing damage should the mechanism be inadvertently electrified.

D. PROCUREMENT AND FABRICATION

Procurement of the components in the P-FMA drives was simplified by direct copy or modification of the P-FMA purchase orders. The other components were selected during the design phase by trade studies which considered performance, geometry, supplies, qualifications, and cost. Where a good supplier had been identified by competitive bid and successful performance on the P-FMA contract, the same supplier was used. Otherwise, competitive bidding or specific manufacturer's part numbers were used.

Component required dates were established based on the overall schedule. Supplier performance was quite satisfactory despite some schedule problems which could be worked around. A listing of electrical components is given in Table III-4. The other major supplier was Schwartz Precision Gear Co. of Warren, Michigan.

Because of design similarity of the three P-FMA drives, many machined details were made from a common machine setup in order to improve productivity. Details were rough-machined then brought to final external dimensions. In order to incorporate precision into the drives, final gear shaft centers and bearing diameters were located and finally machined using jig bore precision within ± 0.0002 inch. All specified details were then irridited for corrosion control. By completely irriditing these parts, significant time otherwise required for masking was saved. Subsequently, the external finishes were easily applied. The forearm segment was manufactured from standard square extruded aluminum tubing. The translation members were made up from machined fittings, channels, and riveted face sheets. Machined details were inspected for dimensional compliance to engineering drawings.

The various ETU subassemblies and drive assemblies are shown in Figures III-10 and -11, after painting and before final assembly. All drive assembly operations were performed on laminar flow benches within a clean room. All parts had been previously cleaned. Bearings were cleaned ultrasonically prior to being lubricated. The initial assembly phase involved the installation of gears and bearings into the center internal housing. All bearings were installed with a light "push" fit. The two adjustable gears were located and doweled to minimize the gear backlash. At this point, component installation and electrical wire routing were performed concurrently. The motors with matching brush ring assembly were installed on the input shaft. The tachometers with matching brush ring assembly were then installed on the same shaft. The fail-safe brake was installed with its housing and cover to complete one side of the P-FMA-type drive. On the other side the potentiometer and associated anti-backlash gearing were installed, coming off the final output pinion shaft. The potentiometer housing or cover was then installed. As components were installed they were wired in accordance with engineering schematics and wiring diagrams. Each drive has two main connectors--one for power conductors and the other for signal conductors--mounted to the fixed portion of the drive housing. These connectors were subsequently mated with the respective main wire harnesses during final assembly.

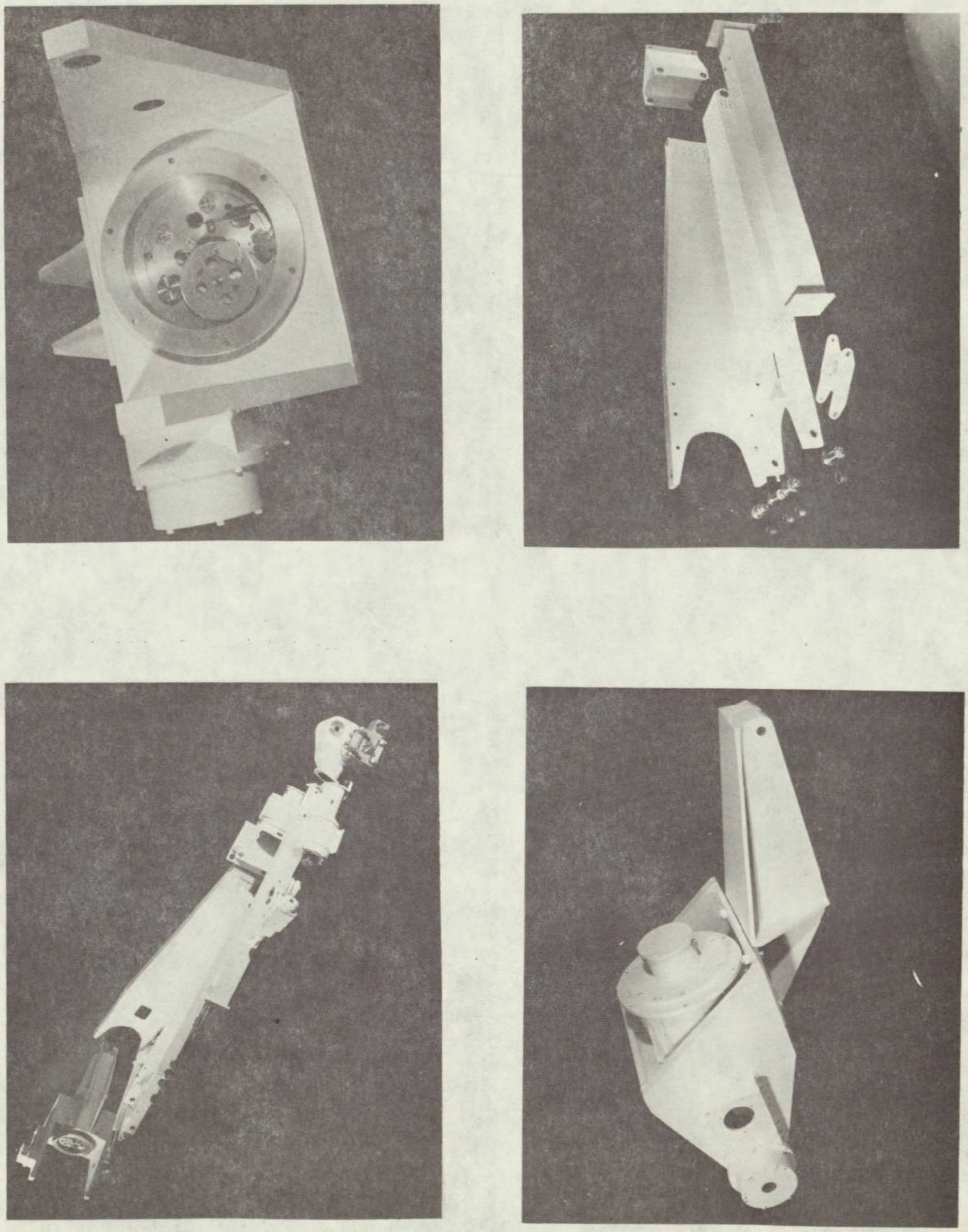


Figure III-10 ETU Sub-assemblies

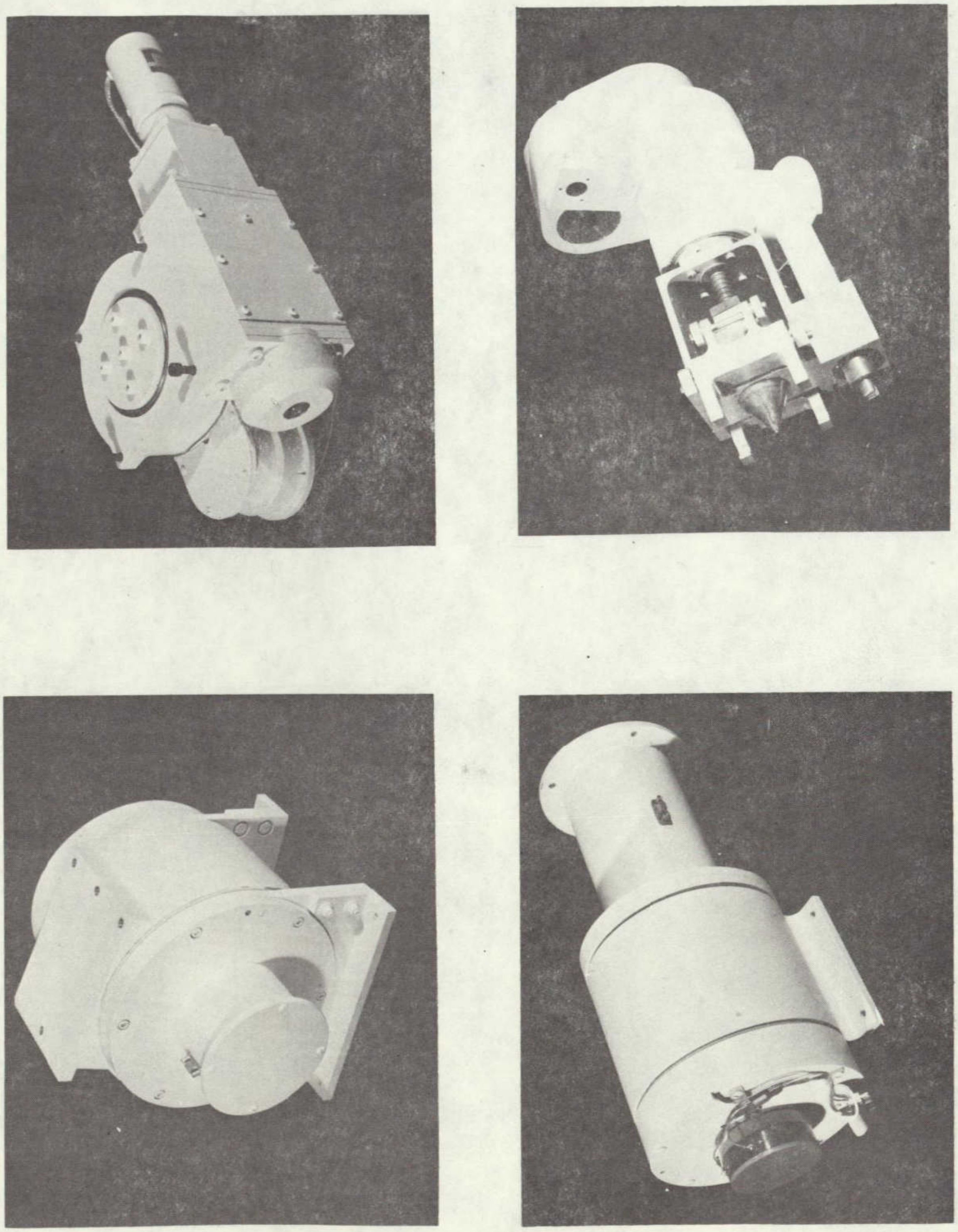


Figure III-11 ETU Drive Assemblies

At this point, interim tests were conducted to verify electrical continuity and resistance, and the functional performance of each drive. The drive assembly procedures for the shoulder pitch, wrist yaw, wrist roll, and the end effector are different due to their unique designs. However, the assembly philosophy and tests are similar.

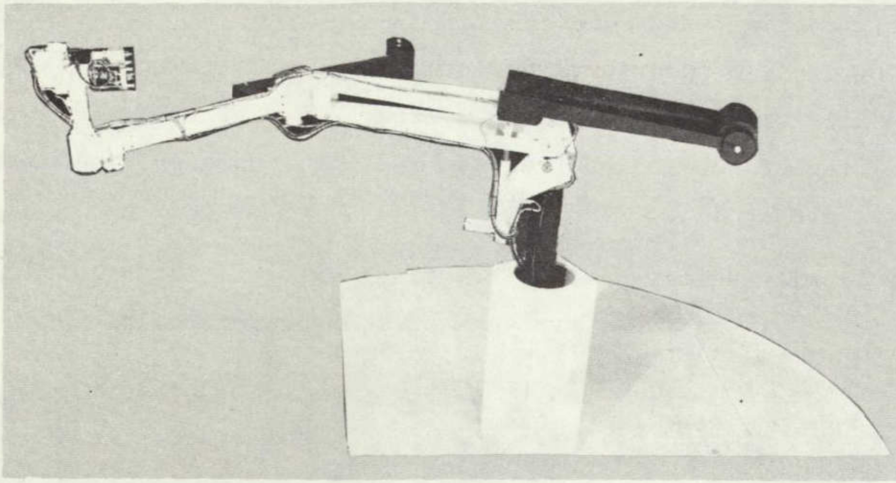
Just prior to final assembly of the ETU, final external chip-resistant finishes were applied to the drives, arm segments, and counterbalance components.

E. ASSEMBLY AND CHECKOUT

The final assembly of the ETU progressed, starting from the support stand, to the shoulder roll drive, to the shoulder pitch, and so on throughout the length of the arm. When mechanical assembly of the servicer was complete, a preliminary counterbalance was established. The outer part of the ETU from the elbow roll drive was removed and temporarily mounted horizontally so it could be balanced using a test case of wrist drive angles and interface mechanisms. The components were then reassembled and the shoulder counterbalance was established. The completely assembled servicer is shown in Figure III-12.

The main wire harnesses were developed, routed, and clamped in accordance with the engineering schematics. The next operation was to set the arm in its nominal position and null the potentiometer in each drive joint. Then each drive was operated through the specified angular travel and the limit switches were set at the position extremes. The counterbalances were then final-adjusted. Backlash in the shoulder pitch drive and shoulder pitch drive current in the up vs the down direction were used to evaluate counterbalance acceptability for a range of forearm positions.

The ETU was checked out as an assembled unit before mating with the SSDC and control system. Each joint was subjected to the same general test.



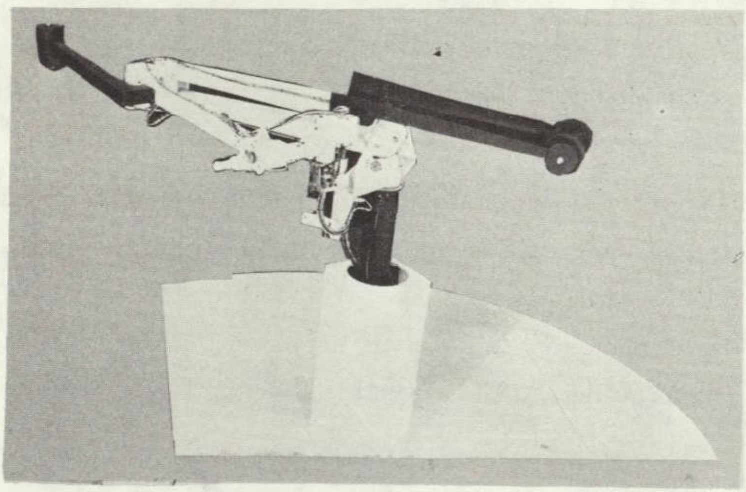


Figure III-12 Assembled Servicer Mechanism

These tests included operation to limits, minimum rates, starting currents (both directions); tachometer signal polarity, scale factor, and noise level; potentiometer zero, polarity, scale factor, and noise level; brake operation, and limit switch operation. Additionally, the end effector jaw motor, latch motor, and limit switches were checked for proper operation. The TV camera, auto-iris lens, and end effector lights were also checked for proper operation and alignment.

IV. SERVICER SERVO DRIVE CONSOLE

The servicer servo drive console (SSDC) is a self-contained electronics system which contains all the functions to permit operation of the one-g servicer system in the manual direct control mode. It also provides the proper interfaces to a digital computer to permit operation in the supervisory and manual augmented control modes. The electronics are housed in a standard rack as shown in Figure IV-1. A precision digital voltmeter has been provided at the top of the console. This voltmeter can access all the test points in the system using the selector switches on the servo drive panel (SDP). This panel provides for individual control of each motor and brake as well as control of all together.

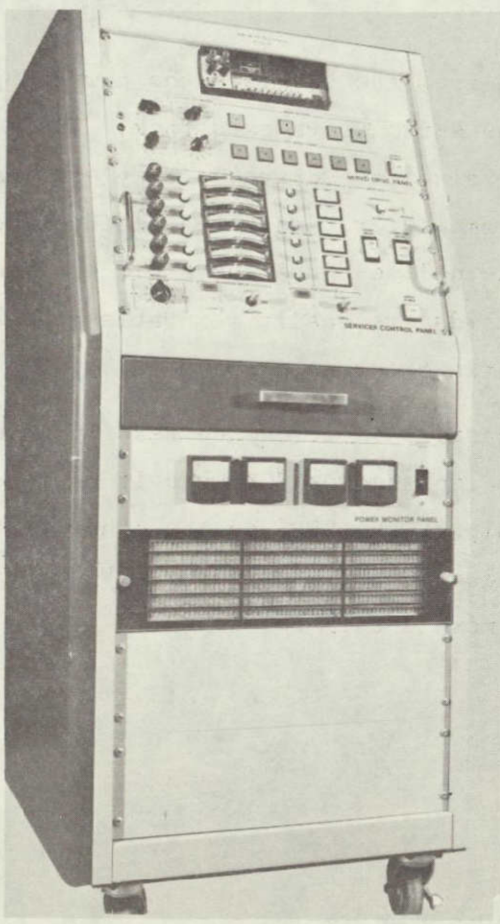


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Figure IV-1 Servicer Servo Drive Console

The servicer control panel (SCP) has all the controls for the manual direct mode as well as the computer interface controls. The SCP can be removed from the SSDC and installed in a remotely located (100-ft cable) control station. The SCP also has a servo power switch that can be used to shut off all the servos and apply the brakes.

Beneath the combined drawer and writing desk is the power monitor panel (PMP) which displays voltage and current for the self-contained high current power supplies. The PMP has a circuit breaker which is also used as the basic ON/OFF switch. This single switch shuts down and turns on *all* power to the SSDC and the ETU. It can be used as an emergency, safety, and daily shut-off switch. The only external power required is 30 amps of 60 Hz, 115V power. All other types of power are generated within the SSDC itself.

Within the console and accessible from the back are the power supplies, servo power amplifiers, and the servo drive card rack. There are individual amplifiers for each of the six servo drives. They each have two stages; a commercially available amplifier, and a transistor bridge. Each of the servo drives has two dual-in-line cards which process the various electronics signals. These cards are easily removable and can be mounted on extender cards for ease in troubleshooting.

The SSDC is mounted on lockable casters so it can be readily moved around. A plain panel is provided to replace the SCP when it is removed for remote operation. The relationship of the SSDC to the other parts of the servicer system is shown in the block diagram of Figure IV-2. Each of these interfaces are discussed in more detail below.

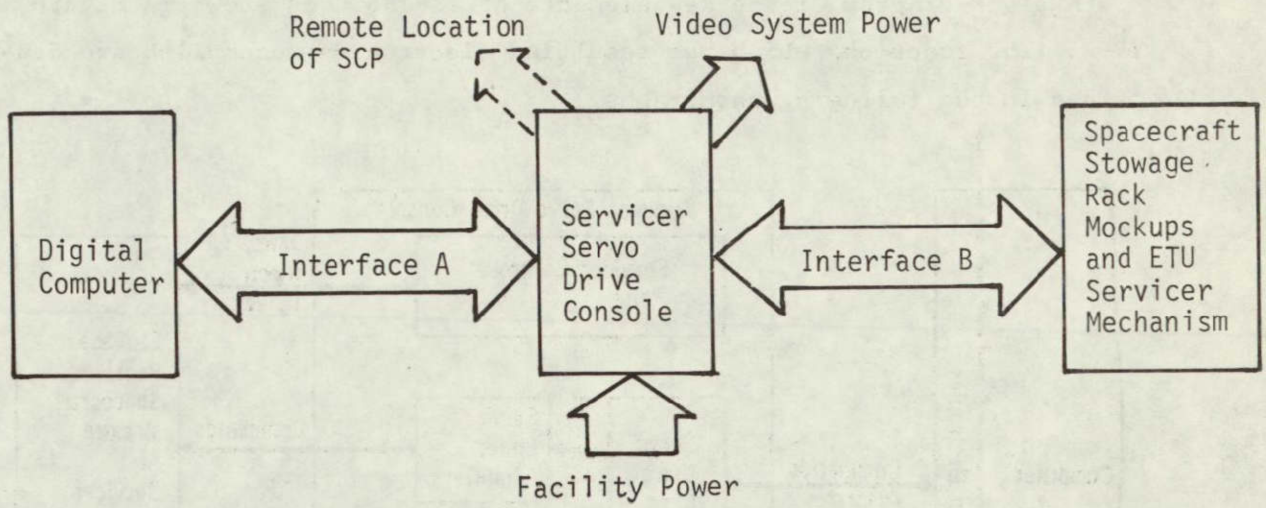

Figure IV-2 Servicer Servo Drive Console Interfaces with One-G Servicer System

A. FUNCTIONAL DESCRIPTION

The SSDC was specifically designed to satisfy the requirements of the MSFC one-g servicer system facility. A set of requirements was prepared and published. The latest version of these requirements is Martin Marietta report, *Servicer Servo Drive Console Design Requirements*, March 3, 1978, Rev. B. The general requirements identified a single vertical type console with easily removable components. Circuit design and fabrication is of the breadboard type--low cost and highly accessible. All SSDC incoming and outgoing signals are protected by buffering electronics. The SSDC is compatible with the six DOF ETU and the three modes of control--supervisory, manual direct, and manual augmented. It also accommodates both axial and radial removal and replacement of space replaceable units (SRU), or modules. The control system is compatible with demonstrations of the total system both at Martin Marietta, Denver, in the Space Simulator Laboratory, and at MSFC using the SEL 840 computer and teleoperator facility base of the MSFC Electronics and Control Laboratory.

A block diagram of the key elements of the SSDC is shown in Figure IV-3. The functions which the resulting electronics accomplish are described in the following paragraphs.

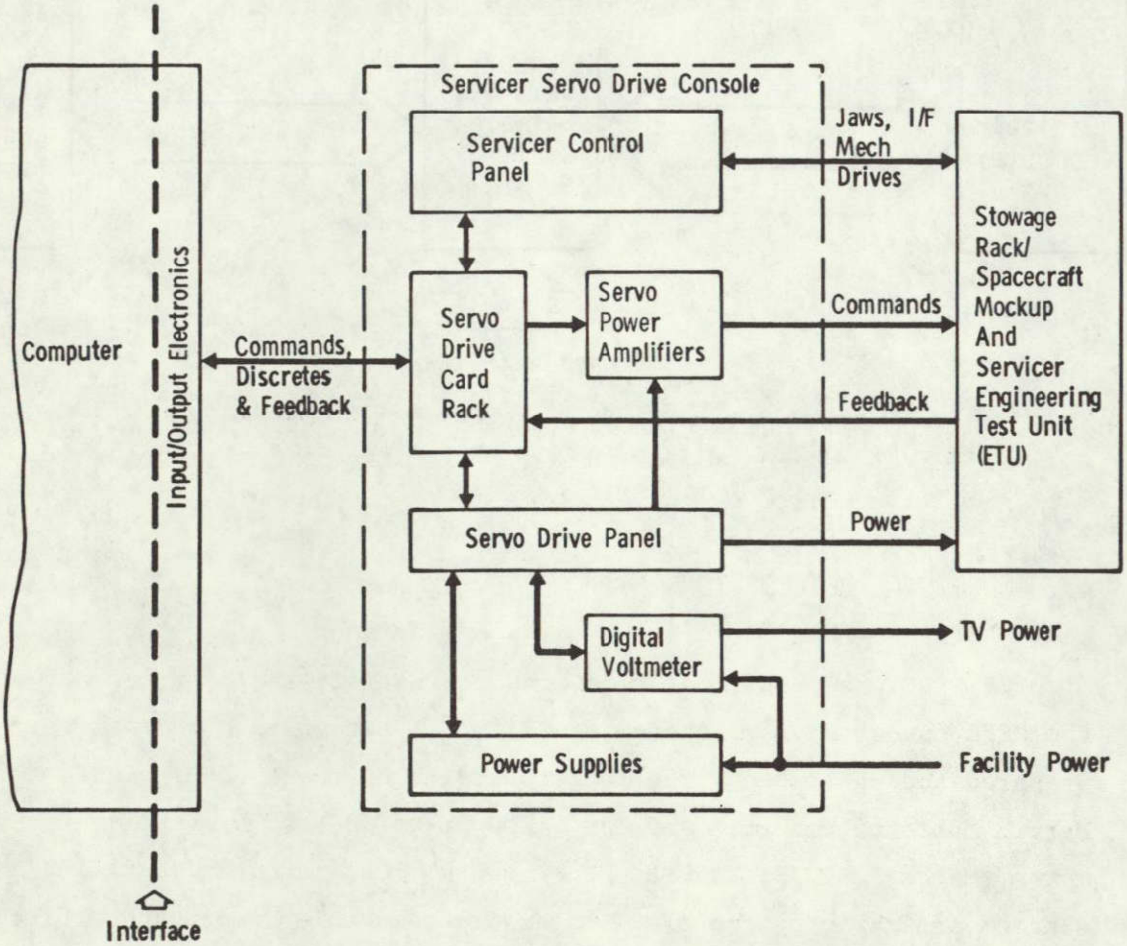

Figure IV-3 SSDC Key Elements

1. Digital Voltmeter

The digital voltmeter, shown in Figure IV-4, allows easy monitoring of numerous test points within the SSDC. External input connections are also provided for measurement of additional signals. The digital voltmeter (DVM) is a Fluke Model 8800A with an accuracy of ± 0.005 percent of full scale. In addition to the DC voltage measurements in the SSDC, it can also measure resistance and AC voltages. The DVM panel also has a card which identifies the specific test parameters for the

selector switch positions of the SDP. An ON/OFF switch for the closed circuit TV camera and the end effector lights is also included on this panel.

2. Servo Drive Panel

The servo drive panel is also shown in Figure IV-4. The panel contains a number of switches whose functions are described.

a) Servo Power - A master servo power switch which turns all servo power to the individual joints and to the joint brakes on and off. This switch is in series with a similar switch on the SCP. Both must be on for the servos to operate. *These switches should be used in any emergency involving joint motion.* They cause a rapid discharge of the servo compensation network capacitors which reduces the amplifier output to

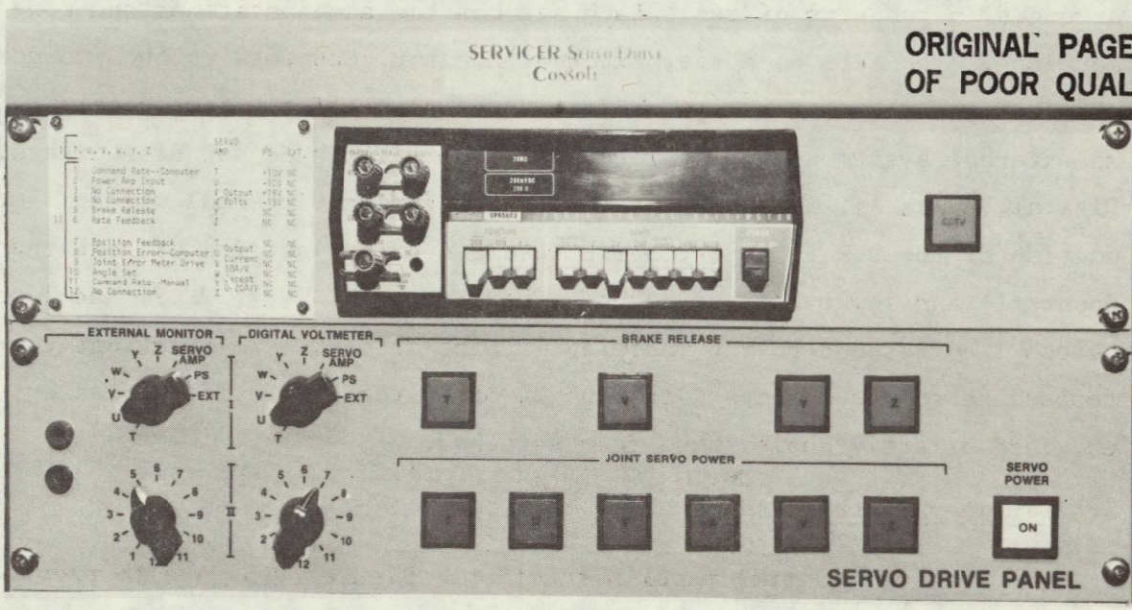

Figure IV-4 Digital Voltmeter and Servo Drive Panel

zero very quickly and allows the brakes to engage. Use of any other emergency shutdown method may result in slow decay of the compensation network capacitors and a continuation of joint motion. This is particularly hazardous if an unbalanced module is being supported by a wrist drive servo.

b) Individual Joint Servo Power - These six switches are used to connect and disconnect their respective joint drive motors from the associated servo drive amplifier. The switch indicator lamp goes on when the switch is in the ON position. However, the servo motors will not run unless *both* the joint servo power and the servo power (a) above) switch lamps are on.

c) Brake Release - These four switches are used to override the automatic brake release logic for the backdriveable joints. That is, the brakes can be released in either of two ways. The switch indicator lamp goes on when the switch is in the ON position. However, the brake release function will not operate unless *both* the joint servo power and the servo power (a) above) switch lamps are on.

d) Test Point Multiplexing Network - These four rotary switches are arranged in two sets of two. Each set has the same positions and connections. The left hand set, External Monitor, connects to the two adjacent test jacks and can be used to connect any of the test points to an external system such as a recorder. The right hand set of switches, Digital Voltmeter, is connected to the DVM through internal wiring. Connection of the DVM to a test point requires proper setting of both the upper (I) and lower (II) switches. The letters T, U, V, W, Y, and Z on Switch I correspond to the individual joint drives. The functions corresponding to the numbers 1 through 12 of Switch II are identified on the card directly above these four switches.

3. <u>Servicer Control Panel</u>

The servicer control panel's functions (Figure IV-5) are to provide control mode selection, controls and displays for manual direct control of the arm, manual control of the end effector operations, module location selection, computer control functions, and servo power control. The servicer control panel is removable, and cables are provided for operation from a remote location. A blank panel is provided to cover the hole in the SSDC when the SCP has been removed.

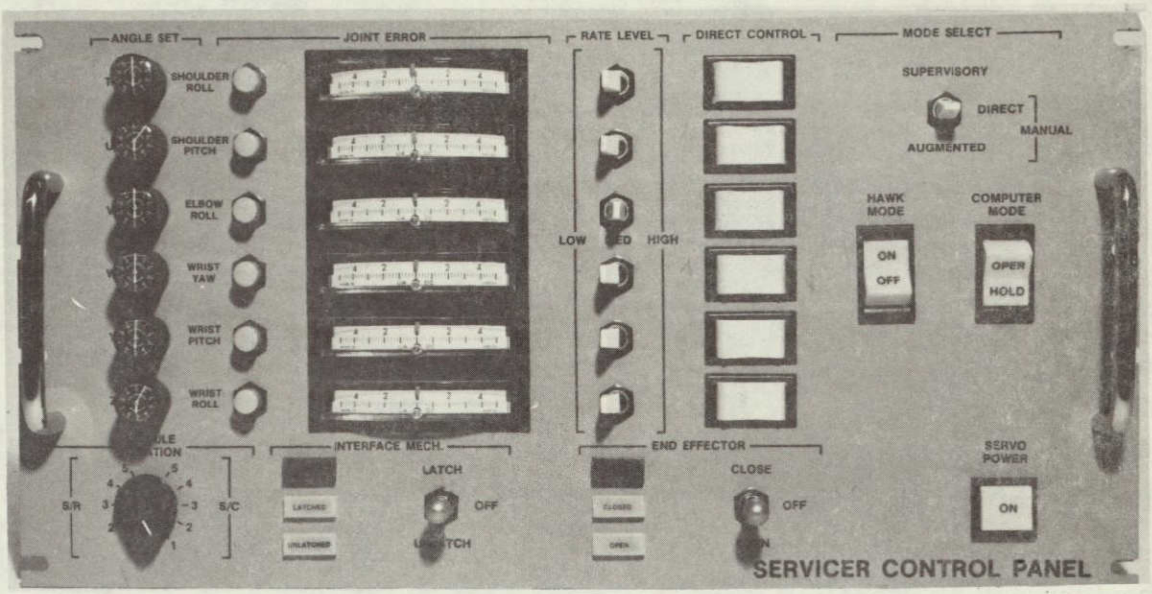

Figure IV-5 Servicer Control Panel

The majority of the SCP functions are self-explanatory except for the manual direct control mode functions. A separate row of controls and displays are assigned for each servicer mechanism degree of freedom. These are labeled with the joint name and symbol (e.g., shoulder roll - T) and are ordered starting from the top of the panel and the base of the mechanism, going down and out respectively. The desired joint angle is set on the ten-turn *angle set* potentiometer. The *joint error* light goes on if the angle error is greater than 0.1 deg, while the *joint error* meter reads the error in degrees up to ± 5 deg and then limits. *Rate level* switches are provided to select *low, medium*, and *high* joint rates. The *direct control* spring-loaded, three position, rocker switches initiate joint motion at a rate corresponding to the level selected. The *joint error* meter and *direct control* motions are coordinated in that if it is desired to have the meter needle move left, then the left side of the *direct control* switch is depressed. Each joint works in the same way.

4. Power Monitor Panel

The power monitor panel is shown in Figure IV-6. It contains the master power circuit breaker which is used as the normal ON/OFF switch. As all other forms of power are derived from the 60 Hz line, the master

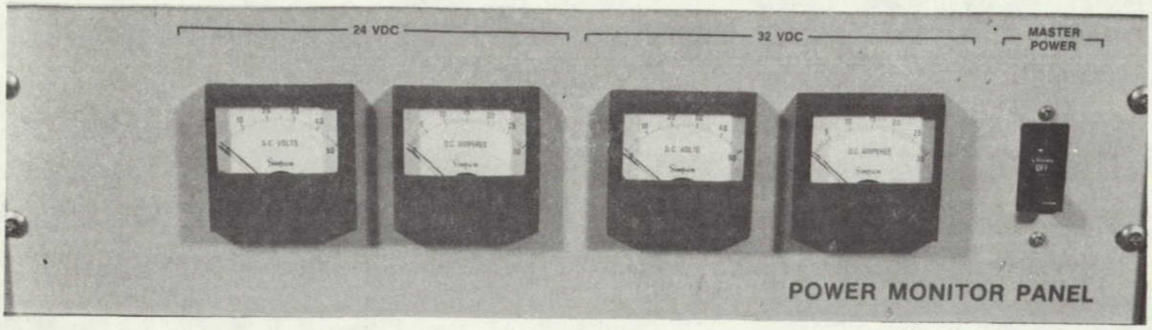

Figure IV-6   Power Monitor Panel

power switch controls the incoming 60 Hz power directly. Voltage and current meters are provided for the 24V DC and 32V DC supplies. The normal condition (no joints operating) is for neither supply to exceed one ampere.

5. <u>Servo Drive Card Rack</u>

A rear view of the servo drive card rack is shown in Figure IV-7. There are two cards (A and B) for each degree of freedom, starting with

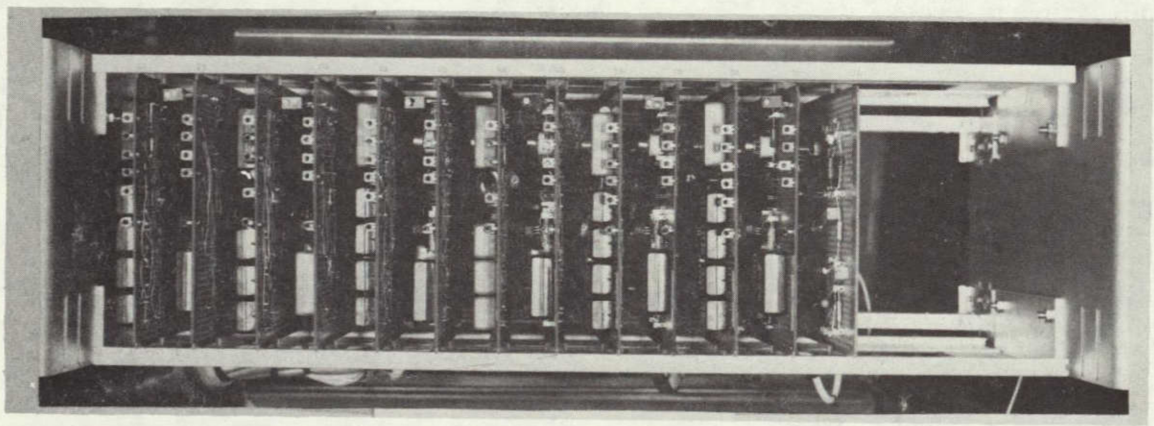

Figure IV-7   Servo Drive Card Rack

TA on the left, then TB, UA, etc. The thirteenth card is the $\pm$10V DC precision power supply which is used for the SCP angle set and servicer mechanism feedback potentiometer excitation. Both the + and - 10 volt levels are individually adjustable. The servo drive card rack forms the heart of the control system. Its functions are to:

1) Signal condition the angular position (B card) and rate feed-

back (A card) signals from the servicing mechanism and commands from the Servicer Control Panel (A card) for internal use by the control electronics;

2) Interface information to and from the computer system (A and B Cards);

3) Generate the discretes to control the joint brakes (A card), and operational mode (A card);

4) Provide networks to individually tailor each joint's loop gain characteristic to obtain optimum system performance and stability margins (A card);

5) Generate signals for the error meters and lights on the Servicer Control Panel (B card);

6) Provide for joint motion corresponding to the rate levels selected on the Servicer Control Panel (A card);

7) Provide for signal switching as a function of the control mode selected (A and B cards);

8) Provide joint direction sensing (B card) and motor control in response to limit switch action (A card);

9) Provide for fast decay of loop gain networks when servo power is turned off (A card).

Each card can be individually removed and remounted on extenders for easy access to all components during troubleshooting. Each of the test points is brought out to color coded test jacks on the rear edge of the cards. The only adjustments are for the servicer mechanism feedback potentiometer gain. The adjustments are on the upper rear edge of the B cards where they are readily accessible.

6. <u>Servo Power Amplifiers</u>

The six servo power amplifiers are mounted on the inside of the console rear door as shown in Figure IV-8. They are multiple stage high power linear amplifiers with sufficient capacity to drive the related

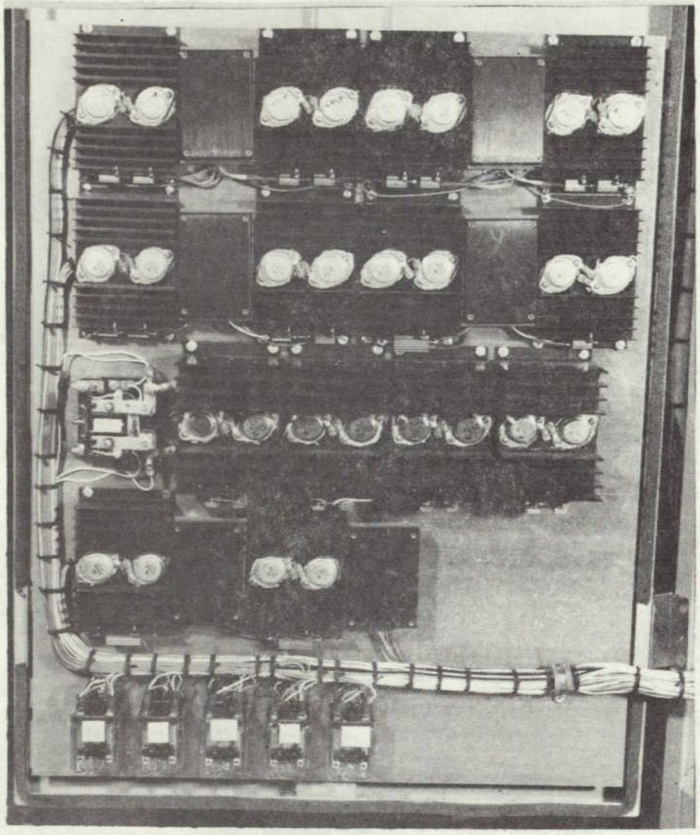

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Figure IV-8 Servo Power Amplifiers

DC torque motor. Each axis uses the same type of Inland EM1801 amplifier for the first stages of gain. The amplifier voltage gain and effective impedance are individually tailored for each axis. The high power stages are transistor bridges driven from the Inland amplifiers with one transistor in each leg of the bridge except for the shoulder pitch (U) drive which uses parallel transistors in each leg because of the 20 ampere current requirement. Current measuring and limiting resistors are included in the bridge circuitry.

7. DC Power Supplies

A 24V DC high current supply is used to operate relays, light lamps, and power all the servo motors. An 8V DC high current supply is connected in series with the 24V DC supply to provide the 32V DC required to drive some of the servo motors. A ±15V DC supply is provided to power

the integrated circuits on the cards of the servo drive card rack and the resistor networks of the manual direct rate command system.

B. DESIGN

A detailed block diagram of the SSDC is provided in Figure IV-9 which is generally arranged as is the console itself. Within the servo drive card rack, the upper half corresponds to the A cards and the lower half to the B cards. The following discussion will describe the design features of the key circuits in the block diagram. Full details of all the SSDC electronics circuitry is contained in MCR-78-535, *SSDC Electronics Identification,* March 15, 1978, Martin Marietta Corporation, Denver, CO.

1. Servo Drive Card Rack

The rate (A cards) and position error (B cards) commands from the computer are received by differential amplifiers with a common connection to the computer ground. A typical receiver amplifier is shown in Figure IV-10. Connection of the amplifiers in this manner provides

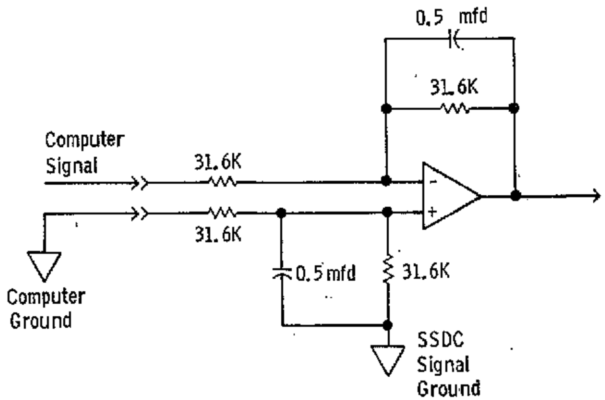

Figure IV-10 Computer Input Differential Amplifier

FOLDOUT FRAME 1

FOLDOUT FRAME 2

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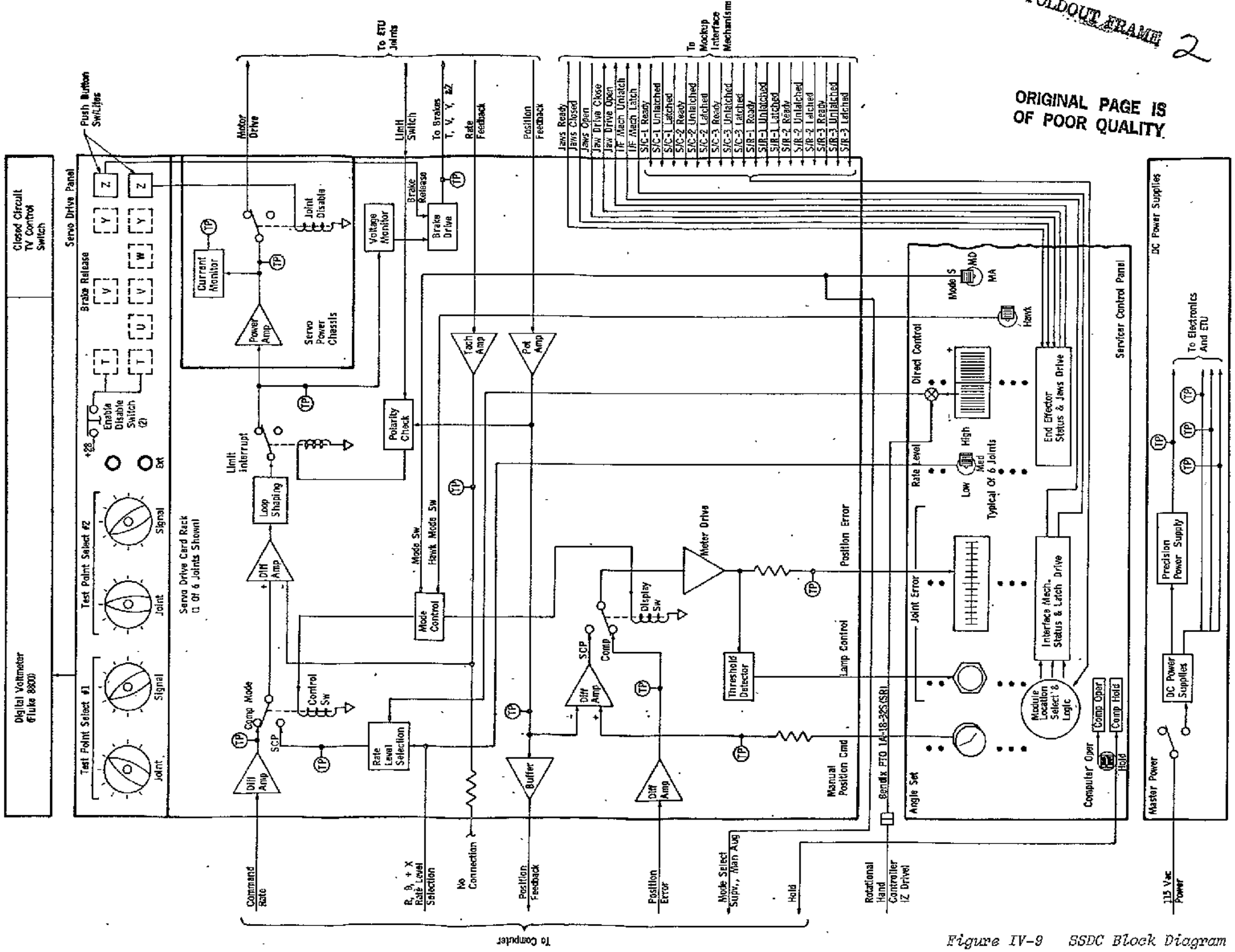


Figure IV-9 SSDC Block Diagram

ground isolation between the computer and the SSDC to minimize ground loop currents, and provides a significant reduction in the number of wires required in the cabling between the computer and the SSDC. A 10 Hz first order low pass filter is included in the receiver design to eliminate high frequency line noise.

A similar design is used to buffer the position feedback signals (B cards) to the computer. Figure IV-11 illustrates a typical SSDC output buffer. This design provides the same ground isolation as the receiver amplifier and eliminates the need for a second driver to achieve full differential operation. The signal also can be received at the computer with a single ended receiver, rather than requiring a differential unit.

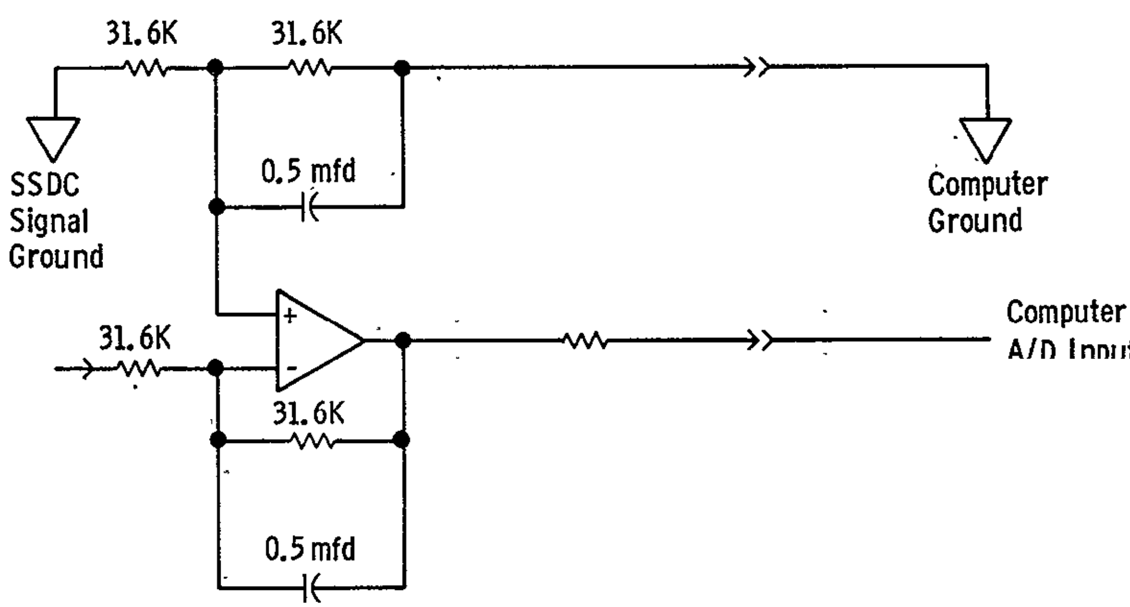


Figure IV-11 SSDC Output Buffer

Position feedback is obtained via the potentiometers installed in each servicer mechanism joint. The potentiometer outputs are buffered (B cards) before being used in the control electronics. Figure IV-12 illustrates a typical potentiometer buffer amplifier with its scale

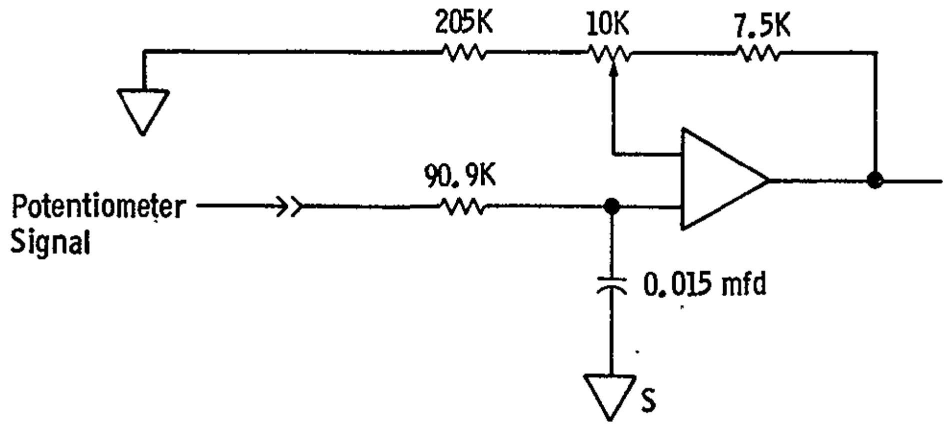


Figure IV-12 Position Feedback Buffer Amplifier

factor adjustment resistor, R8. The filter components are chosen to provide a 10 Hz roll off for noise attenuation. The gains are set individually to yield the scale factors listed in Table IV-1.

Table IV-1 Joint Position Output Scale Factors

Joint	Scale Factor	Range
T	0.05 volt/deg	±200 deg (±10V DC)
U	0.333 volt/deg	±30 deg (±10V DC)
V	0.10 volt/deg	±100 deg (±10V DC)
W	0.10 volt/deg	±100 deg (±10V DC)
Y	0.05 volt/deg	±200 deg (±10V DC)
Z	0.05 volt/deg	±200 deg (±10V DC)

The rate feedback signals from the joint tachometers are buffered by a circuit (A cards) which is essentially the same as the position feedback amplifiers. The gains of the rate feedback buffer amplifiers are individually set to match the output level of the tachometers, yielding the output scale factors shown in Table IV-2. These same scale factors also apply to the computer generated rate commands which were discussed previously.

Table IV-2 Joint Rate Scale Factors

Joint	Scale Factor	Range
T	0.02 rad/sec/volt	±0.2 rad/sec (10V DC)
U	0.015 rad/sec/volt	±0.15 rad/sec (10V DC)
V	0.03 rad/sec/volt	±0.3 rad/sec (10V DC)
W	0.01 rad/sec/volt	±0.1 rad/sec (10V DC)
Y	0.04 rad/sec/volt	±0.4 rad/sec (10V DC)
Z	0.04 rad/sec/volt	±0.4 rad/sec (10V DC)

The manual angle set potentiometer outputs from the SCP are summed with the joint position feedback signals to produce the error meter drive signal (B cards) in the manual direct mode. The schematic for this circuit is shown in Figure IV-13. In the other control modes the

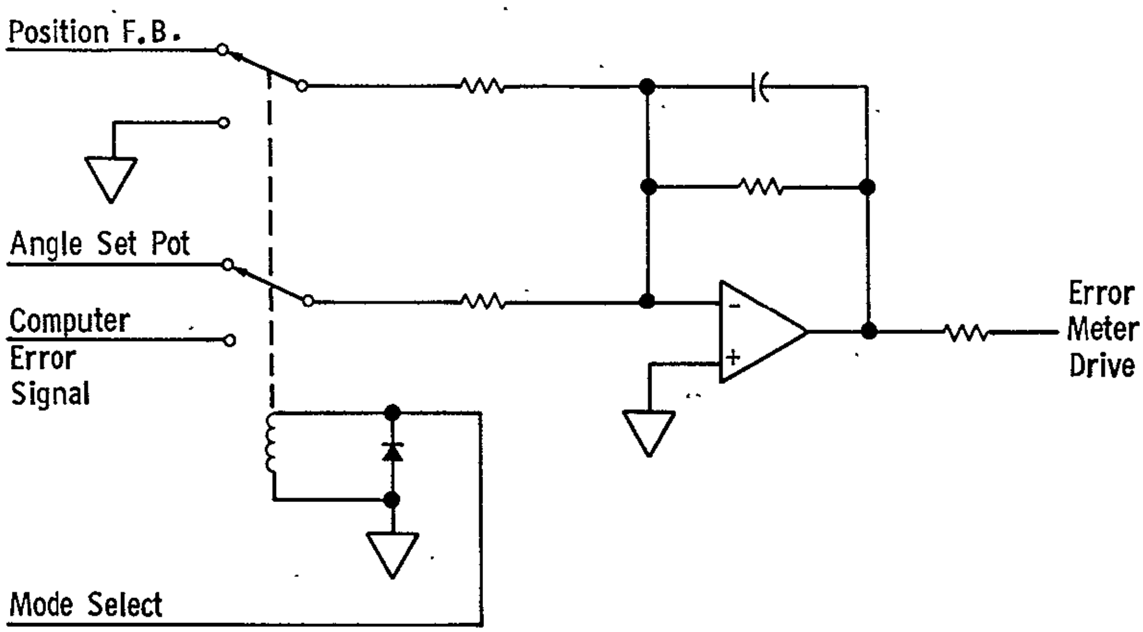


Figure IV-13 Error Meter Drive Circuit

error meter drive signal comes from the computer. The signal source selector is a DIP relay controlled by the mode select switch. The selector connects the computer-generated, or SSDC-generated, error signal to the meter drive amplifier for the appropriate modes. Table IV-3

Table IV-3 Error Meter Drive Source

Joint	Mode Select Switch Position		
	Manual Direct	Supervisory	Manual Augmented
T	Angle Set Pot	Computer	Angle Set Pot
U	Angle Set Pot	Computer	Angle Set Pot
V	Angle Set Pot	Computer	Angle Set Pot
W	Angle Set Pot	Computer	Angle Set Pot
Y	Angle Set Pot	Computer	Computer*
Z	Angle Set Pot	Computer	Computer*

*If the Hawk Mode switch is OFF, the signal source is the angle set potentiometer rather than the computer.

lists the error meter drive source for the three positions of the mode select switch. The outputs of the error meter drive amplifiers go to the error meters on the SCP panel and to the error threshold detection and lamp drive circuitry (B cards). This circuitry is shown in Figure IV-14

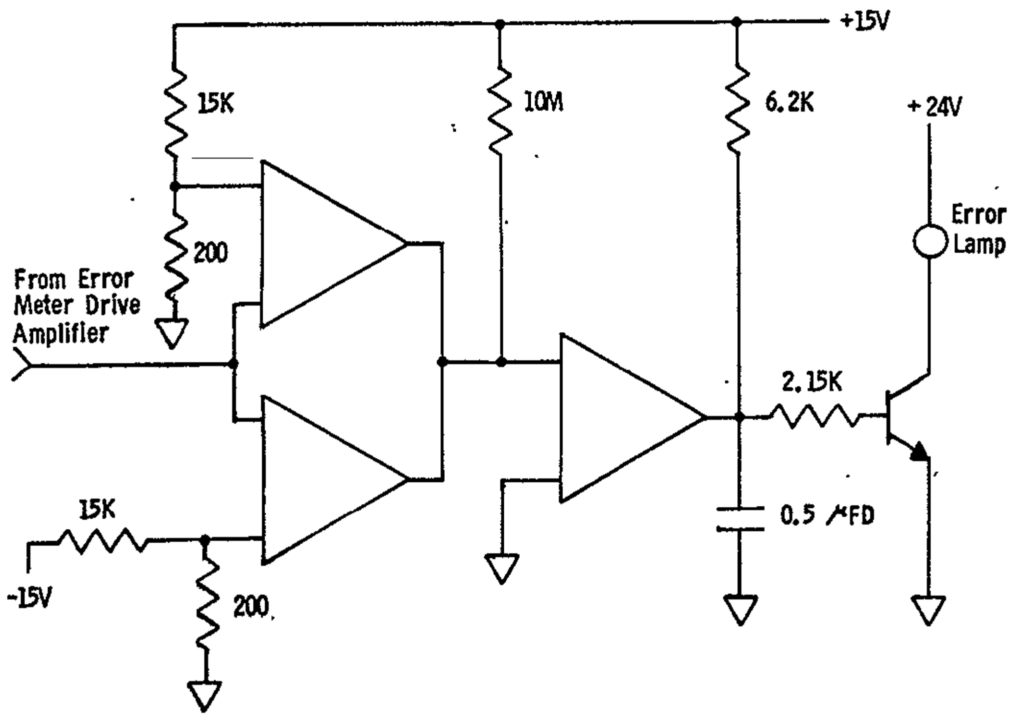


Figure IV-14 Joint Error Lamp Drive Circuitry

and it operates so the joint error lamps on the SCP go on whenever the corresponding joint error exceeds an absolute value of 0.10 deg. Otherwise the lamps will be off.

Each joint has a single limit switch (except for the Wrist Yaw, W, joint which has two switches wired in parallel to act as a single switch) which operates at either end of the allowable range of travel. The limit signal is fed to the limit interrupt circuitry (A cards) which monitors the state of the joint's limit switches. When the limit switch is activated the input to the servo power amplifier is zeroed which stops the joint motion. Once tripped the limit switch circuitry will only respond to a signal of opposite polarity, allowing the joint to be backed off from the limit. The limit switch logic is implemented using three DIP relays to open the normal circuit path. Diodes across the relay contacts provide the capability to back off the limits. The polarity of the joint limit is determined by monitoring the feedback potentiometer signal (B cards).

The loop shaping networks (A cards) provide for adjustment of the gains, poles, and zeroes required for proper servo compensation. The circuits are individually tailored for the requirements of each servo axis. The servo transfer functions are defined in Section C of this chapter of the report.

The four backdriveable joints (T, V, Y, and Z) are fitted with normally engaged (fail safe) brakes. That is, with current off the joints will not move. These joints can be released by providing current from either of two sources. The manual release circuitry was described in paragraph IV-A-2. The automatic release circuitry (A cards) is similar to that for the joint error lamps (Figure IV-14) except that relays are provided to isolate the circuitry from the inductance of the brake solenoids. The brake control circuitry sensing line comes from the same point as the servo motor power amplifier input. The circuit constants are adjusted so the brakes will be released whenever the sensed voltage amplitude exceeds 0.5 volts. Note that electrical power must be applied and the brake release switches operated before the backdriveable joints can be moved manually.

2. Servo Power Amplifiers

Power amplifiers are the final gain stages used to drive the motors. The design incorporates Inland EM 1801 power amplifiers driving high current transistor output circuits which provide the power capability required. A linear design was chosen to preclude the EMI generated by pulse width modulated switching schemes. Figure IV-15 illustrates a simplified schematic of a typical power output stage. The motor dis-

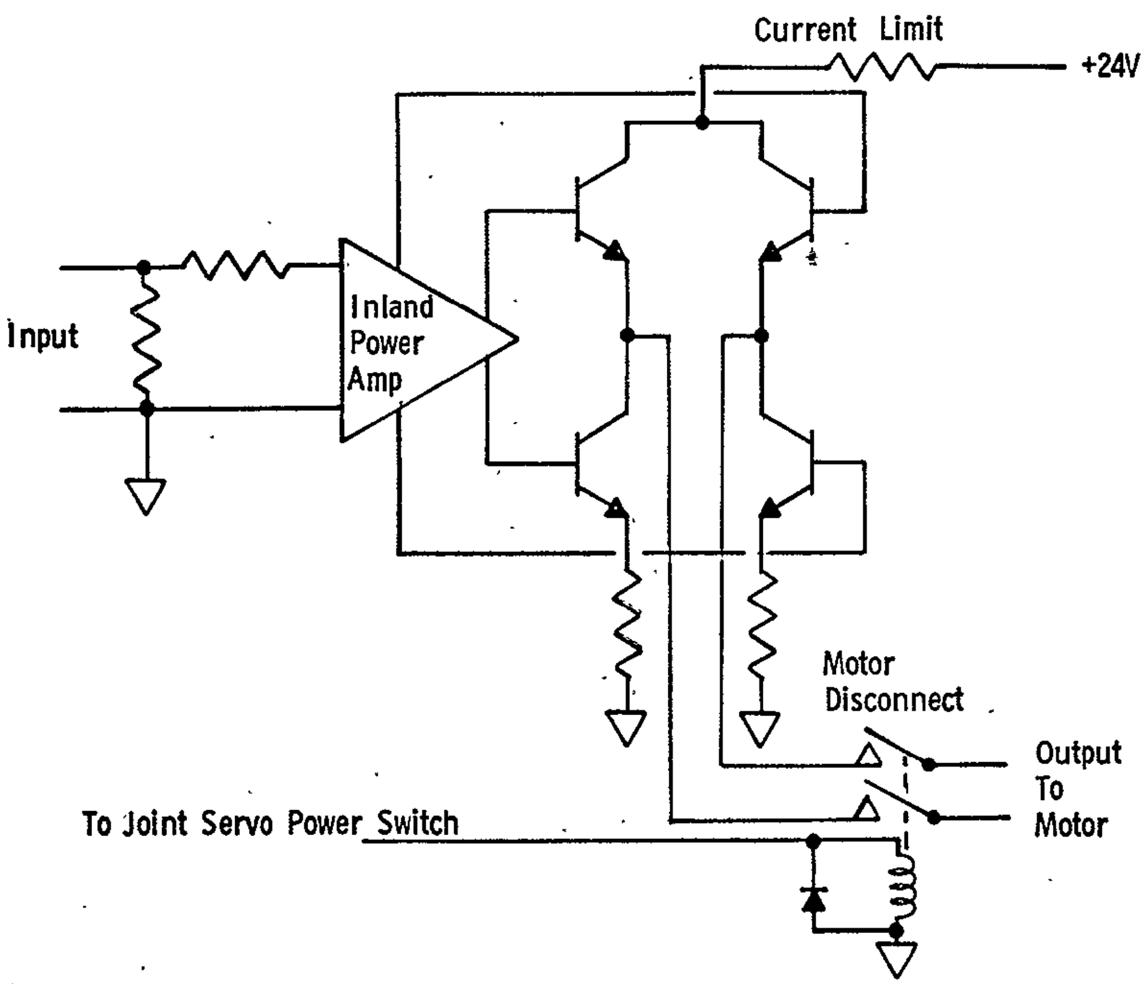


Figure IV-15 Power Output Stage

connect shown in the figure is a power relay which is operated by a switch on the power control panel. It is normally open and must be

energized to connect the power amplifier to the motor armature. Current limiting resistors are provided to limit motor current and thus avoid degaussing the motor permanent magnets and overheating the motors. The output transistors are paralleled in the U joint drive circuitry to provide the power required. While not shown, both voltage and current feedback from the transistor bridge to the Inland amplifier are used to control gain and output impedance of the stage. Motor voltage and current monitoring leads are also provided. The resistors at the bases of the lower transistors are the current measuring shunts.

3. Servicer Control Panel

The three-position mode select switch sends signals to the A and B cards and to the computer so the various signals are processed properly. It is also interconnected with the hawk mode switch so the proper functions are displayed on the joint error lamps and meters. The rate command sources are:

Manual Direct - SCP Angle Set Potentiometer
Supervisory - Computer
Manual Augmented - T, U, V from Computer
W, Y from SCP
Z from SCP or Rotational Hand Controller.

The joint angle error display signal sources as a function of control mode are given in Table IV-3. Use of the control mode signals in the computer are discussed in *Servicer Simulation Software Requirements*, Rev. C, February 27, 1978, Martin Marietta Corporation, Denver, CO.

The manual rate command signals are generated in the SCP and sent to the servo drive card rack. The direct control switches and rotational hand controller connect the ±15V supply into resistor networks and then to the rate loop summing amplifiers on the A cards. The three-position rate level switches control the resistor network configurations to provide the correct voltage levels. The specific rate levels are given in Table IV-4.

Table IV-4 Manual Command Rates

Joint	Rate Level Switch Position		
	High	Medium	Low
T	0.1 rad/sec	0.05	0.017
U	0.07 rad/sec	0.035	0.017
V	0.14 rad/sec	0.07	0.017
W	0.1 rad/sec	0.05	0.017
Y	0.21 rad/sec	0.1	0.035
Z	0.21 rad/sec	0.1	0.035

Second sets of resistor networks are associated with the T, U, and V rate level switches. These networks provide three different voltage levels to the computer during the Manual Augmented mode so the rates resulting from translational hand controller action may be selected.

A computer mode switch on the SCP provides two different voltage levels to the computer which may be used to control the computer's operating mode.

The module location switch is used to select which set of signals will be applied to the interface mechanism status lamps. The *ready* and *unlatched* signals are derived from microswitches on the interface mechanism receptacles, while the *latched* signal is derived from the mating of the interface mechanism electrical connector. There are three spacecraft (S/C) active locations (positions 1, 2, and 3). There are four stowage rack (S/R) active locations. Three of these (1, 2, and 3) are separate cables while the fourth position is jumpered to position three.

Both the interface mechanism switch and the end effector switch are center (off position) locked and must be lifted to be operated. This is to avoid inadvertently dropping a module during an exchange. Both switches control relays in the SSDC which in turn control the motors in the end effector. The relays were added to avoid the line voltage drops when the SCP is remotely located.and they are located on an interface connector chassis which is on the lower part of the left hand side

of the SSDC. Resistor networks are used to generate three voltage level signals to indicate the status of the interface mechanism switch. These signals are sent to the computer to initiate a 1-3/4 inch module movement during the latch and unlatch motions. Three microswitches are provided in the end effector to generate the signals for the end effector jaw status lamps.

4. DC Power Supplies

The DC power supply set consists of a +24V DC and a +8V DC high current power supply to provide power to the joint motors and a ±15V DC dual supply to power the control electronics. In addition to these commercial supplies a reference voltage generator derives precise ±10V DC from the ±15V DC supplies. This precision reference voltage source is used to power the position feedback and joint angle set potentiometers. This provides a stable reference for use in the servicer control system. Each supply is internally protected against direct shorts on the output and is case grounded to avoid hazards to personnel.

C. SERVO SYSTEM ANALYSIS

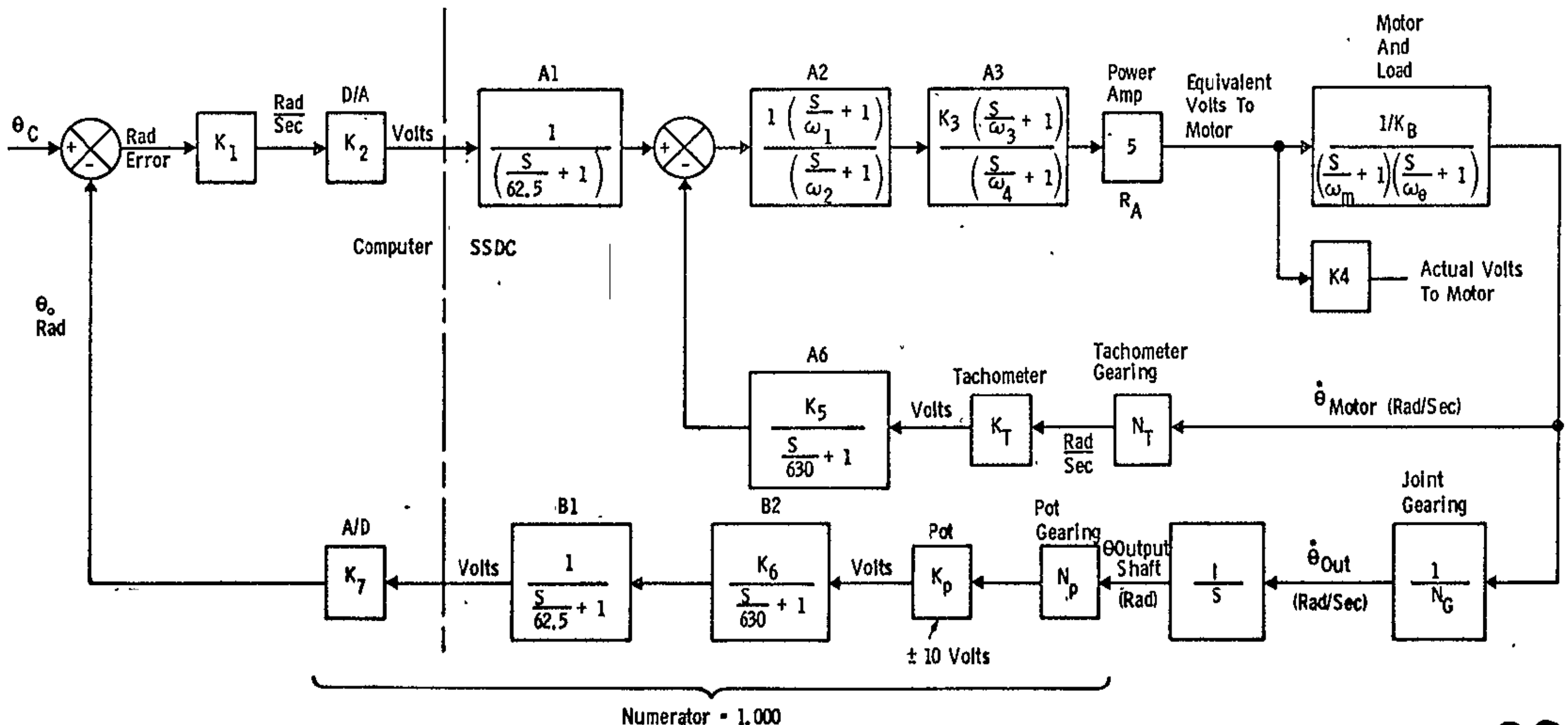
The design of a servo system involves two major aspects--performance and stability. For the servicer system the important performance parameter is steady state position error when in the supervisory mode. Only the rate loop is analyzed for the manual modes as the position loop is closed through the man and he can adjust loop gain (his response) to obtain the desired error and stability. Speed of response is not extremely important as the time for one module exchange has been set at ten minutes. Normal operation will involve motion through most of a trajectory at constant velocity (limit value) and then a slow decay to the final position. This approach was used during the January/February 1977 simulation and proved very successful.

In line with the slow response concept, it was also decided to limit system bandwidth to less than 1 Hz. This will tend to separate the structural natural frequencies and the servo loop frequencies. Not only will this simplify the servo analysis, but it will avoid unnecessary increases in struc-

tural stiffness and weight.

As noted above, the design of a one-g system is quite different from the design of a zero-g mechanism. As full mass modules cannot be picked up in one-g, the one-g system sees lower inertias and thus higher frequencies with regard to module masses. However, the one-g mechanism has counterbalance arms and weights added. These arms and weights increase system inertias and thus lower the bending frequencies. Because they are attached differently and the counterbalance arms are designed differently, they also change mode shapes--all of which strengthens the decision to keep the control loop band-pass below the structural natural frequencies.

A block diagram of the transfer function for any one of the ETU joints is shown in Figure IV-16. As the rate--or inner--loop must operate alone in the manual mode, it will be stabilized by itself. Then stability will be obtained for both loops operating together. The "known" parameters of Figure IV-16 are shown in Table IV-5 for each joint. Note that Figure IV-16 shows lag filters on several amplifiers. All amplifiers have high frequency cut-off filters, but only those which might have influenced the servo design (< 10 Hz) are shown. The objective of the servo analysis is to determine values for K_1, K_3, ω_1, ω_2, ω_3, and ω_4 for each servicer mechanism degree of freedom.



K_1 - Position Loop Gain
K_2 - Digital To Analog Converter Gain
K_3 - A_3 Amplifier Gain
K_4 - Motor Resistance Ratio
K_5 - A_6 Amplifier Gain
K_6 - B_2 Amplifier Gain
K_7 - Analog To Digital Converter Gain
K_T - Tachometer Scale Factor
K_P - Potentiometer Scale Factor

K_B - Motor Scale Factor
N_G - Joint Gear Ratio
N_P - Potentiometer Gear Ratio
N_T - Tachometer Gear Ratio
R_A - Power Amplifier Output Resistance, ohms
S - Laplace Transform
ω_1, ω_2, ω_3, ω_4 - Corner Frequencies (Rad/Sec) Of Compensation Function
ω_e - Motor Electrical Corner Frequency (Rad/Sec)
ω_m - Motor Mechanical Corner Frequency (Rad/Sec)

Figure IV-16 Joint Transfer Function Block Diagram

Table IV-5 Joint Transfer Function Parameters

Joint	K_2	K_4	K_5	K_6	K_7	K_T	K_P	K_B
Shoulder Roll T	50	0.820	1.941	1.044	0.349	0.235	3.274	0.45
Shoulder Pitch U	66.7	0.500	1.683	1.060	0.0524	1.200	3.274	95.3 *
Elbow Roll V	33.3	0.820	1.295	0.890	0.1745	0.235	3.274	0.45
Wrist Yaw W	100	0.857	8.511	0.986	0.1745	0.235	3.274	3.92†
Wrist Pitch Y	25	0.896	1.032	0.972	0.349	0.235	3.274	0.42
Wrist Roll Z	25	0.704	0.585	0.972	0.349	1.200	0.318	0.34

*Data referenced to drive output shaft

†Data referenced to worm shaft

Joint	N_G	N_P	N_T	R_A	ω_e	ω_m		
						EE Only	Side Mech	Base Mech
Shoulder Roll T	109.6	0.837	1	0.6	1330	1.14	0.86	0.82
Shoulder Pitch U	1	5.5	33	0.2	500	8.32	6.65	6.23*
Elbow Roll V	109.6	1.965	1	0.6	1330	4.82	3.41	3.37
Wrist Yaw W	50	1.776	1	0.6	1330	29.6	28.5	27.0 †
Wrist Pitch Y	103.1	0.90	1	0.6	680	37.1	23.4	16.7
Wrist Roll Z	35.56	9.26	1	0.6	810	71.4	34.9	17.3

See Figure IV-16 for definition of symbols and units.

1. Unbalanced Moments

The joint error for a position loop depends on the unbalanced moment, or motor starting torque, and the position loop gain. This paragraph discusses the unbalanced moments. Weights for each component of the ETU were determined, either by weighing the subassembly or by estimation. These weights are listed in Table IV-6. The counterbalance weights were determined as part of the analysis. Locations for each weight were also estimated.

Three cases were evaluated:

1) End effector only;
2) Side interface mechanism attached; and
3) Base interface mechanism attached.

For the end effector only case, the drive angles were selected to obtain minimum unbalance moments while the drive angles were selected to give maximum unbalanced moments for the interface mechanism cases. Unbalanced moments were computed for each drive. For the elbow roll drive, twenty-two representative cases were used to determine a best estimate of elbow counterbalance

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Table IV-6 ETU Component Weights

ITEM	WEIGHT (lbs)
1. Side Interface Mechanism with Module Mockup	23.5
2. Base Interface Mechanism with Module Mockup	30.6
3. TV Camera and Lights	6
4. Z Drive plus End Effector	22.5
5. Y Drive	15
6. W Drive	12
7. Outer Arm	5.5
8. V Drive	20.7
9. Elbow Counterbalance Arm	6
10. Elbow Counterbalance	TBD
11. Inner Arms	32.4
12. U Drive	53.6
13. Shoulder Counterbalance Arms	28
14. Shoulder Counterbalance	TBD
15. T Drive	21.2

weight and offset--106 lbs and 4-1/2 in. outboard respectively. The use of the elbow counterbalance puts the c.g. of all items outboard of the elbow near the elbow axis. The above 22 cases were used to determine the unbalance to be applied to the shoulder pitch drive.

Note that neither the elbow roll or shoulder roll drives see any unbalanced torque as their axes are vertical. The counterbalances are used to minimize the variation in pitch drive unbalance (elbow) and cancel out the average unbalance (shoulder). The resulting unbalanced moments used for servo system design are listed in Table IV-7. The maximum values relate to the unbalanced moments as determined above. The design value was taken to be the largest unbalanced moment that could occur during module insertion or ten percent of motor torque. The design values were used to determine loop gains. The maximum values (which might occur during the middle of a flip) were used to check motor capability. The worst cases are for the base interface mechanism. During a flip 78% of the Y drive stall torque is required, while during a transition to radial, 83% of the W drive planetary gear reducer rating is required. These percentages can be reduced by selecting the optimum module attitudes to keep the c.g. close to the critical axis.

Table IV-7 Joint Unbalanced Moments (ft-lbs)

Joint	End Effector Only		Side Mechanism		Base Mechanism		Referenced To
	Maximum	Design	Maximum	Design	Maximum	Design	
Shoulder Roll T	0	0.15	0	0.15	0	0.15	Motor Shaft
Shoulder Pitch U*	150	150	143	150	231	230	Screwjack
Elbow Roll V	0	0.15	0	0.15	0	0.15	Motor Shaft
Wrist Yaw W	0.62	0.62	1.48	1.20	2.13	1.76	Worm Shaft
Wrist Pitch Y	0.024	0.085	0.37	0.13	0.66	0.30	Motor Shaft
Wrist Roll Z	0.063	0.25	0.22	0.25	0.82	0.25	Motor Shaft

*Force in pounds

2. Allowable Joint Errors

The allowable joint errors were based on the rule that a joint error should not produce more than one-eighth of an inch of error at the maximum radius with either interface mechanism attached. The 1/8 in. figure is a small part of the most critical case which is a one-half inch tolerance for the interface mechanism baseplate-to-receptacle capture. The resulting allowable joint angular errors are listed in Table IV-8.

Table IV-8 Allowable Joint Errors

Joint	Error (deg)
Shoulder Roll T	0.060
Shoulder Pitch U	0.14
Elbow Roll V	0.094
Wrist Yaw W	0.20
Wrist Pitch Y	0.20
Wrist Roll Z	0.24

3. Loop Gains

The position loop gains must be at least large enough so the motor stall torque generates the design unbalanced moment for a position error less than the allowable. The position loop gain can be divided into two parts--that associated with generating a rate command from the position error (A), and that part associated with generating a motor torque from the rate error (B). The January simulations used an A gain of 2 deg/sec per deg. Preliminary

calculations indicated that the A gain should be raised to 2.5 deg/sec per deg. The servo analysis treated the outer loop as an angle loop. In the supervisory mode a mixture of outer loops are used, e.g. linear distance in the radius comparison and angle in the wrist roll comparison. For the end effector attitude angles, the comparisons are on an angle basis and the servo analysis applies directly. For the translation aspects (r, θ, and x), there is a joint rate transformation that converts the cylindrical coordinate rates to angular rates. As long as the same A gain is used for each component of the cylindrical coordinates, then the rate transformation will make it appear that this same value of A gain occurs in the angle loops. Thus the same value of A gain is used in each of the joint loop servo analyses. The A gain was selected to be 2.5 and is the value of K_1 of Figure IV-16.

The B part of the position gain must be at least large enough so the motor stall torque equals the unbalanced moments for the allowable position errors. The minimum B gains, and the corresponding minimum values of K_3 of Figure IV-16, were determined and are listed in Table IV-9.

Table IV-9 Minimum Position Loop Gains

Joint	B Gain ft lbs/deg/sec	Referenced To	K_3 volts/volt
Shoulder Roll T	1.00	Motor Shaft	4.62
Shoulder Pitch U	657*	Screw Jack	5.42
Elbow Roll V	0.638	Motor Shaft	4.43
Wrist Yaw W	3.52	Worm Shaft	1.77
Wrist Pitch Y	0.600	Motor Shaft	10.2
Wrist Roll Z	0.417	Motor Shaft	3.09

*lbs per deg/sec

While the minimum B gains vary somewhat due to the reference shaft, the K_3 gains are more consistent. The values used for K_3 were selected as part of the loop compensation discussed below. These values are listed in Table IV-10 and in all cases are significantly larger than the corresponding values of Table IV-9.

Table IV-10 Selected Position Loop Gains

Joint	K_1 deg/sec per deg	K_3 volts/volt
Shoulder Roll T	2.5	11.5
Shoulder Pitch U	2.5	10.5
Elbow Roll V	2.5	10.0
Wrist Yaw W	2.5	20.4
Wrist Pitch Y	2.5	17.9
Wrist Roll Z	2.5	5.0

4. Moments of Inertia

The total moment of inertia connected to the output of each drive axis strongly influences the performance and required compensation. Estimates of these moments of inertia were made for each degree of freedom for the same three interface mechanism cases used in the above joint unbalanced moment analysis. The effect of the mocked up modules was included. For each of the three cases, the wrist drives were oriented to produce minimum moments of inertia for the end effector only case and maximum moments of inertia for the side and base interface mechanism cases. The results are shown in Table IV-11.

Note that the U and W joint data are referenced to the output and worm shafts respectively instead of to the motor shaft. This approach simplified the analysis for those joints. The U drive inertias are different in that

Table IV-11 Moments of Inertia (ft lb sec^2)

Joint	End Effector Only	Side Mechanism	Base Mechanism	Referenced To
Shoulder Roll T	0.020	0.026	0.028	Motor Shaft
Shoulder Pitch U	180	220	240	Output Shaft
Elbow Roll V	460×10^{-5}	650×10^{-5}	660×10^{-5}	Motor Shaft
Wrist Yaw W	3.3×10^{-2}	3.4×10^{-2}	3.6×10^{-2}	Worm Shaft
Wrist Pitch Y	30×10^{-5}	48×10^{-5}	68×10^{-5}	Motor Shaft
Wrist Roll Z	29×10^{-5}	60×10^{-5}	121×10^{-5}	Motor Shaft

as U varies, the elements outboard of the parallelogram translate, but do not rotate. Thus only the mr^2 terms are used, where r is the length of the parallelogram. When the outboard elements also rotate, it is necessary to add the effect of rotation about their own center of gravity, as well as the distance to their center of gravity.

One effect of the elbow counterbalance is to reduce the variation in inertia with change in elbow angle. Ideally, the elbow counterbalance would put the c.g. of all elements outboard of the elbow drive right on the elbow drive axis.

5. Loop Compensation

The final step of the servo analysis is the determination of the compensation functions (ω_1, ω_2, ω_3, and ω_4 of Figure IV-16). The approach taken was to keep the position loop bandwidth below 1 Hz, the rate loop bandwidth near 1 Hz, the A gain at 2.5 rad/sec, and the B gains greater than the values shown in Table IV-9. This resulted in compensation functions with high gain at low frequencies and low gain at intermediate and high frequencies.

A preliminary analysis was made using graphical techniques leading to Nichols (gain vs phase angle) charts for both rate and position loops for all six degrees of freedom for the base interface mechanism case. A Martin Marietta Data Systems library general purpose servo analysis computer program (LADCAP) was then used to evaluate the rate and position loops. Program outputs included gain data, phase data, and factored numerator and denominator transfer functions for both the open and closed loop cases. The preliminary analysis was verified and alternative compensations were investigated. The selected compensation functions were also verified for the side interface mechanism and end effector only cases.

The selected compensation function data is shown in Table IV-12. Note that the same compensation function is used for all three wrist degrees of freedom. A gain-frequency (Bode) plot for the compensation network and the motor mechanical time constant (ω_m) for each of the six degrees of freedom for the base interface mechanism case is, shown in Figure IV-17. When the loop gain is added to the data of Figure IV-17 the zero db crossings are focused to occur between 6 and 9 rad/sec. The closed loop response data show

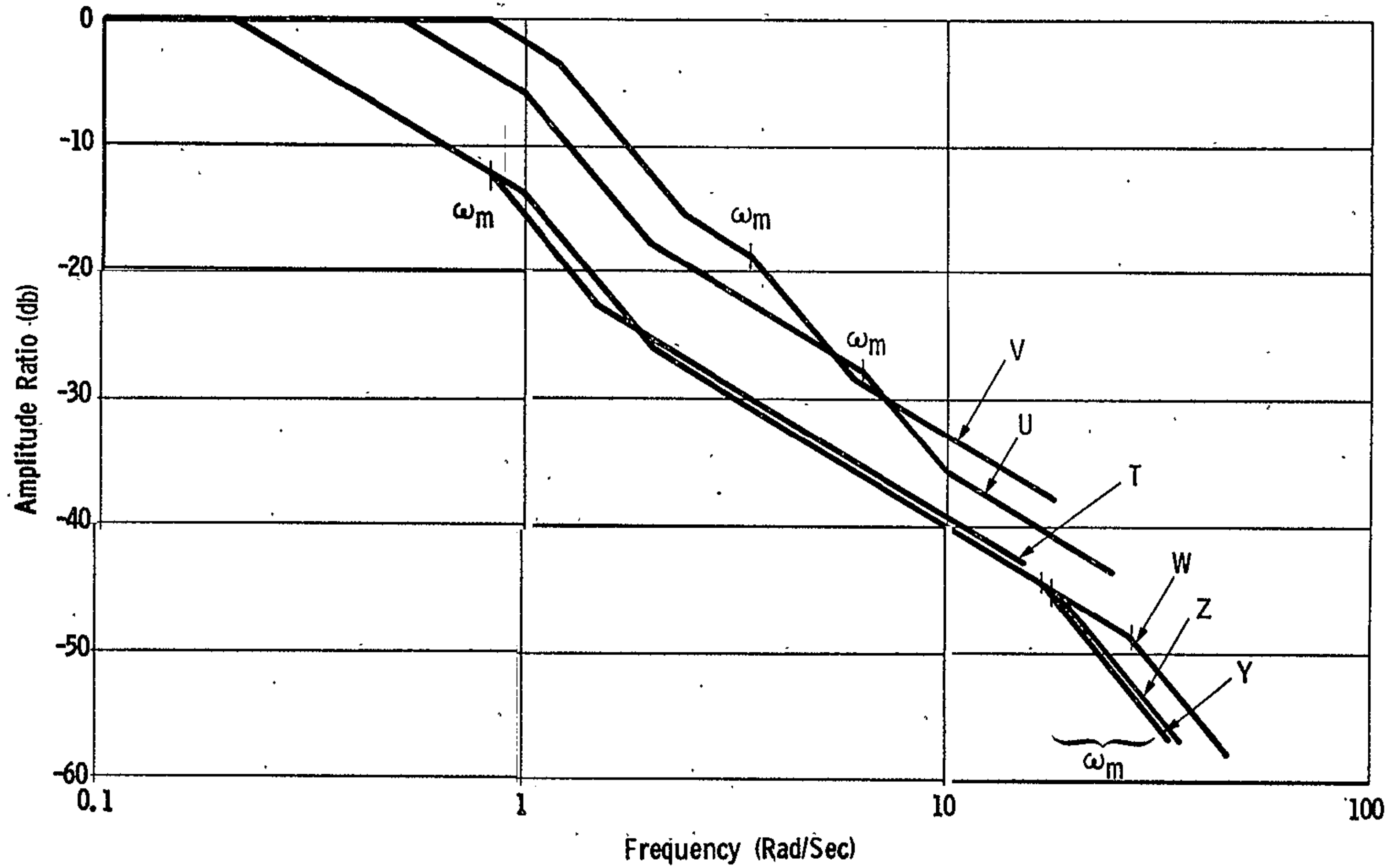

Figure IV-17 Open Rate Loop Transfer Functions

Table IV-12 Selected Compensation Function Corner Frequencies

$$G(s) = \frac{\left(\frac{s}{\omega_1} + 1\right)\left(\frac{s}{\omega_3} + 1\right)}{\left(\frac{s}{\omega_2} + 1\right)\left(\frac{s}{\omega_4} + 1\right)}$$

Joint	Corner Frequencies (rad/sec)			
	ω_1	ω_2	ω_3	ω_4
Shoulder Roll T	1.5	0.2	--	--
Shoulder Pitch U	2	0.5	10	1
Elbow Roll V	2.4	0.8	6	1.2
Wrist Yaw W	2	0.2	--	1
Wrist Pitch Y	2	0.2	--	1
Wrist Roll Z	2	0.2	--	1

a damping ratio of approximately 0.6 for the rate loops and 0.7 for the position loops.

D. FABRICATION

The SSDC is packaged in a movable console. Figure IV-18 illustrates the layout of the major components in the console. The heavy DC power supplies are located in the bottom of the console to keep the center of gravity low. To facilitate moving the console, locking casters have been mounted on its base.

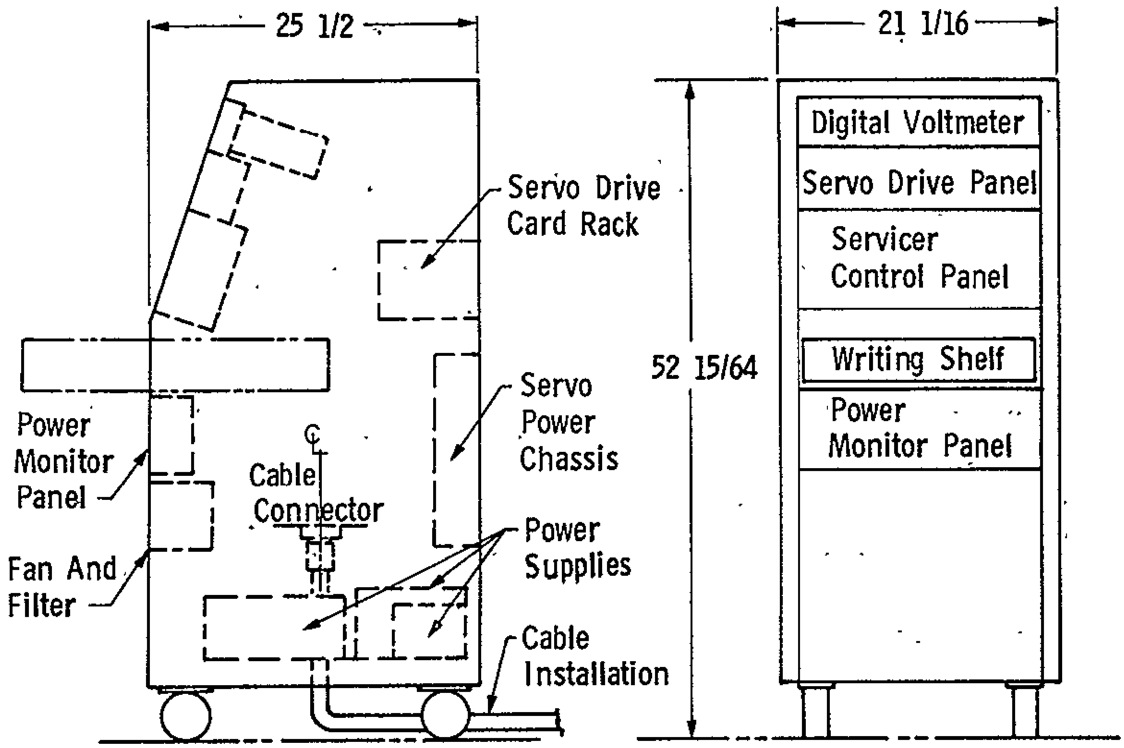

Figure IV-18 SSDC Layout

The small signal electronic components which make up the signal processing section of the console are hand-wired on dual-in-line 4-1/2 in. by 6 in. plugboards. Figure IV-19 illustrates a typical electronics card used in the console. These cards are supported in their own rack and plug into 44 pin card edge connectors to interface with the rest of the system. The circuit cards can be troubleshot in the system from the rear of the console by use of a board extender. All adjustment pots are located in the rear card edge, and all integrated circuits are mounted in sockets for easy replacement. Each test point is brought out to the SDP selector switches and to pin jacks on the card rear edge. These pin jacks are color-coded and the code is defined on a card located on the inside of the console rear door.

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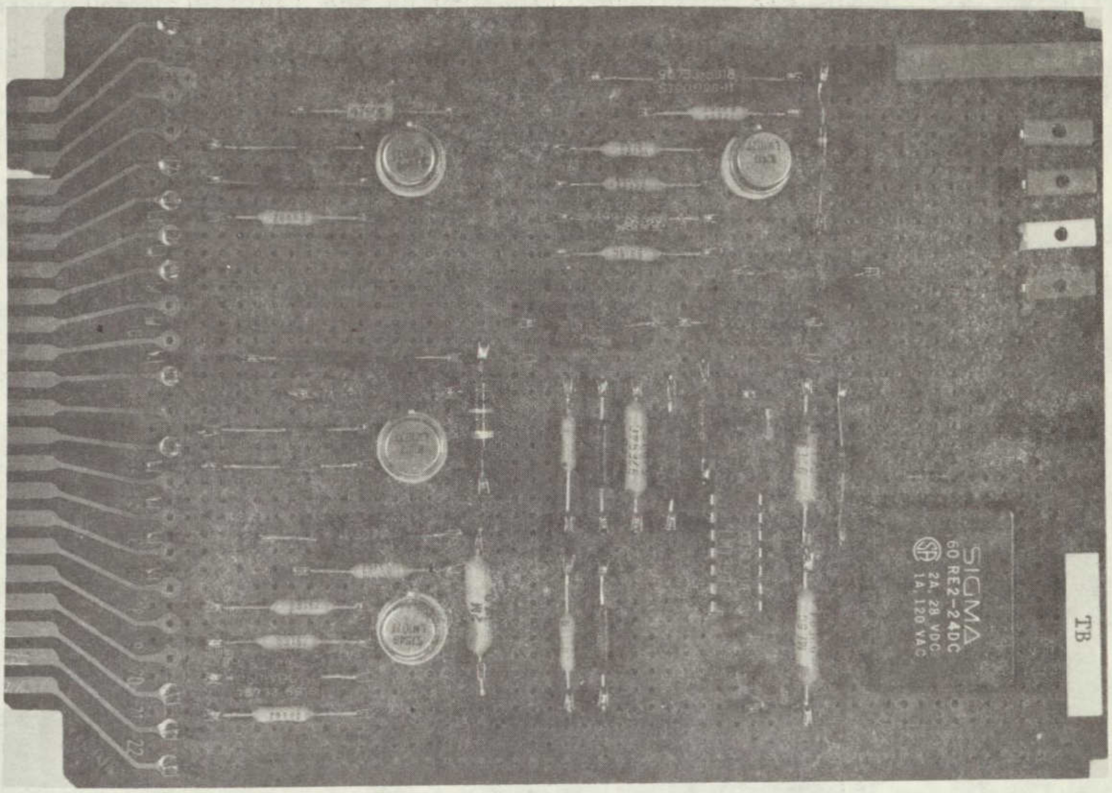

Figure IV-19 Typical Circuit Card

All high power amplifiers, power relays, and current shunts are located on the servo power chassis, mounted on the rear door of the console. Figure IV-8 illustrates the servo power chassis. Forced air cooling from the fan assembly carries the heat generated by this assembly out of the console.

The servicer control panel provides all the controls required for operation of the ETU. This panel is fabricated in a removable chassis for remote operations. Cabling is provided for operation of the control panel with a separation distance of up to 100 feet from the SSDC and a connector is provided for connection to the rotational hand controller. A metal enclosure has been provided around the electronics on the SCP so it is less likely to be damaged during handling.

Each of the six interconnecting cables was fabricated and checked out. The functions in the interface cables A and B of Figure IV-2 are shown in Figure IV-20.

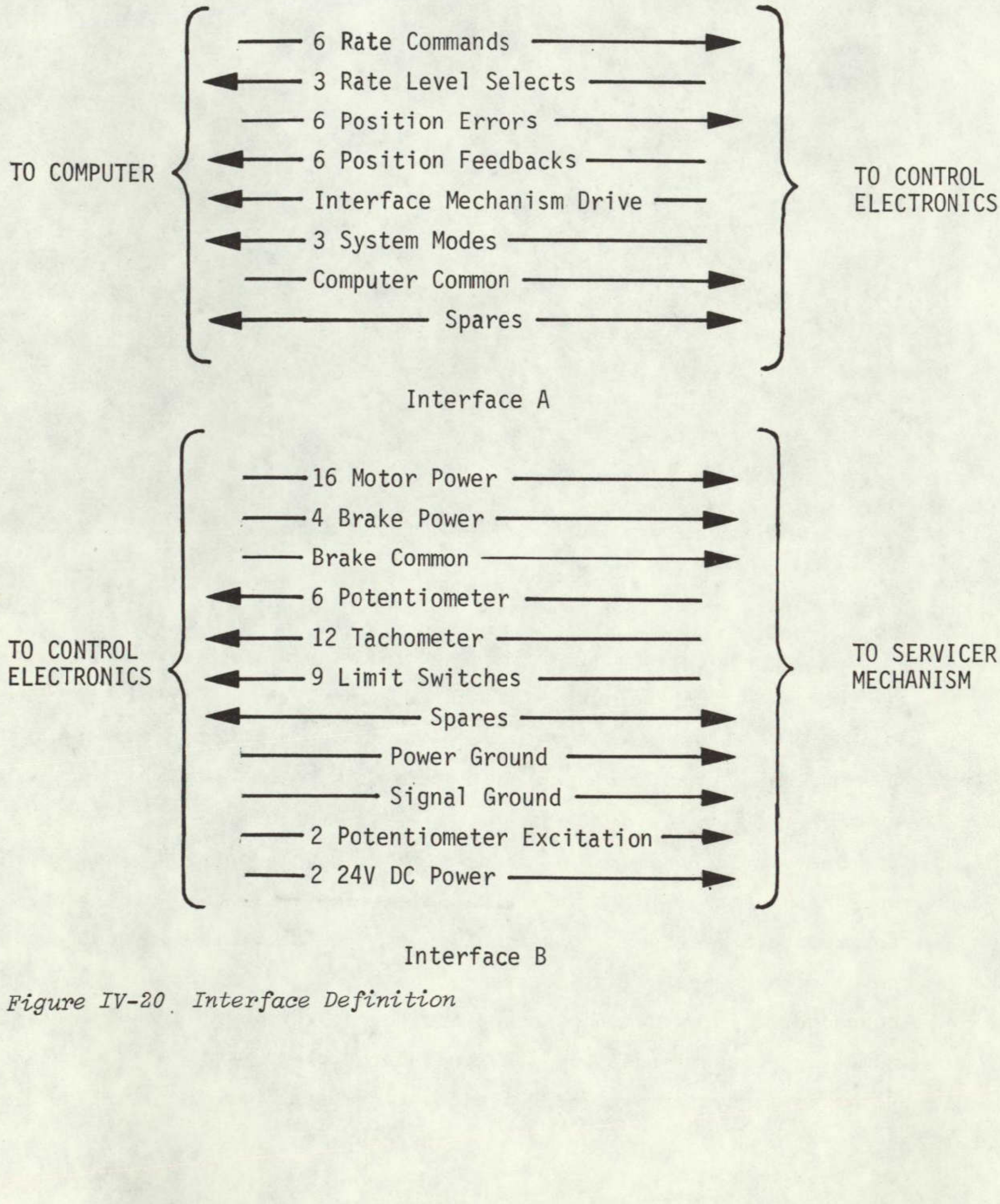

Figure IV-20. Interface Definition

All fabrication and wiring of the SSDC was done by skilled technicians in the Inertial Guidance Laboratory. Each subassembly was checked before being incorporated in the next higher assembly. A set of angle brackets has been provided, along with sufficient cable slack so each panel may be temporarily mounted at ninety degrees to the console for inspection and repair. All parts are of commercial quality and are generally readily available.

The threshold detector circuits and the servo amplifier circuits were breadboarded and tested before the design was finalized. The current feedback, voltage feedback, and current limiting resistors of the servo amplifiers were individually selected during fabrication. Similarly, the operational amplifier resistors were individually selected to provide the desired gain accuracy. Each operational amplifier was verified to have an acceptable offset voltage level before it was used.

E. ASSEMBLY AND CHECKOUT

The SSDC was designed, fabricated, assembled, and tested in-house. As each electronics card was built it was tested individually. The power amplifiers were initially tested under resistive/inductive loads to verify their current output capabilities and adequate heat sinking.

After independent component/function tests, the SSDC components were assembled into the console as shown in Figure IV-21 and the complete control system was tested one axis at a time. A functional checkout procedure was developed detailing the test procedure and expected results, and the actual results were recorded. Discrepancies were noted and corrected as required. The tests included power supply voltage and current; signal, power, and case ground continuity; servo drive panel logic; joint error lamp and meter operation; angle set potentiometer operation; control mode logic; proper signals to and from computer; scale factors; brake release circuitry; amplifier gains; limit switch

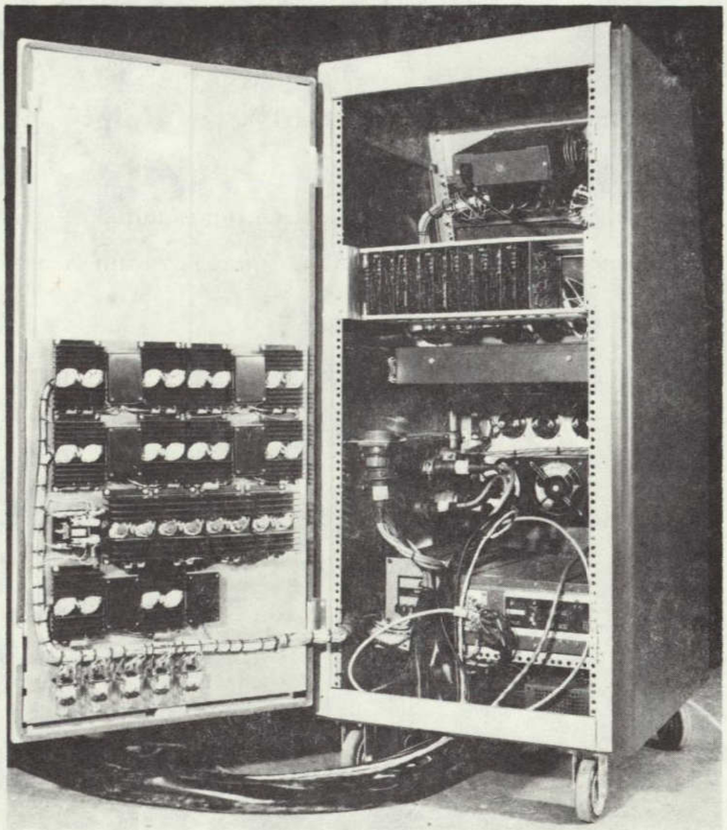

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Figure IV-21 Component Installation in the SSDC

circuitry operation; rate commands; end effector switch and lamp operations; interface mechanism switch and lamp operations; and all other SCP switch operations. For these tests readings were made both at the test points and at connector pins. Thus the DVM and the test point selectors were also checked out.

It was decided not to check signal polarity during the SSDC level tests. This function was left to the SSDC/ETU test phase where complete end-to-end tests could be made and polarities could be checked in a systematic way that minimized the number of wire reversals.

The final testing involved mating of the SSDC with the ETU and performing a complete systems test. This also followed a well-defined test procedure. All operations of the complete system were verified for proper operation.

V. RECOMMENDATIONS

A review of the one-g servicer system design, fabrication, assembly, and test activities identified a number of areas that merit consideration for additional effort. While the system, as delivered, satisfied the contract objectives, the ideas presented here are in the nature of improvements and refinements.

1) System Aspects --

   a) Systematically collect data on the existing systems over the span of control modes, module motion directions, and interface mechanism types.

   b) Investigate a variety of techniques that lead to a reduction in module exchange time.

   c) Examine and refine the manual augmented and manual direct control procedures to obtain more efficient module exchanges.

   d) Investigate techniques for reducing system drift in the manual modes when the modules are subject to unbalanced moments.

   e) Investigate the effects of higher joint rates and control system bandwidths to reduce module exchange times.

   f) Develop better TV target configurations for the radial exchange direction that will aid the operator in selecting proper control actions.

   g) Substitute a local minicomputer for the SEL 840A computer to reduce the effects of the long signal cables and to develop a better understanding of flight unit computer sizing.

2) Mechanical Aspects --

a) Incorporate the Fairchild-Stratos fluid disconnect into the side interface mechanism.

b) Replace the shoulder pitch and wrist yaw drives with units that are more compatible with space operations.

c) Replace the interface mechanism drive motor with a more powerful unit to increase both torque and speed.

d) Revise cable routing at the wrist to maximize combined joint travel.

e) Redesign the interface mechanism baseplates and receptacles to increase the capture volume.

3) Electronics Aspects --

a) Rework brake release logic so brakes engage immediately when AC power is lost or the master power circuit breaker is opened.

b) Investigate better ways to reduce A/D and D/A converter noise at the computer interface.

c) Consider replacement of DIP relays with mercury wetted contact relays or solid state switches.

d) Rework brake release threshold logic for more consistent operation.

e) Provide separate $\pm$15V DC power supply for direct control switch resistor networks to minimize effects on error meters.